

REVIEWS

THE EVOLVING FIELD OF BIODEFENCE: THERAPEUTIC DEVELOPMENTS AND DIAGNOSTICS

James C. Burnett*, Erik A. Henchal†, Alan L. Schmaljohn† and Sina Bavari‡

Abstract | The threat of bioterrorism and the potential use of biological weapons against both military and civilian populations has become a major concern for governments around the world. For example, in 2001 anthrax-tainted letters resulted in several deaths, caused widespread public panic and exerted a heavy economic toll. If such a small-scale act of bioterrorism could have such a huge impact, then the effects of a large-scale attack would be catastrophic. This review covers recent progress in developing therapeutic countermeasures against, and diagnostics for, such agents.

BACILLUS ANTHRACIS
The causative agent of anthrax and a Gram-positive, spore-forming bacillus. This aerobic organism is non-motile, catalase positive and forms large, grey-white to white, non-haemolytic colonies on sheep blood agar plates.

Microorganisms and toxins with the greatest potential for use as biological weapons have been categorized using the scale A–C by the Centers for Disease Control and Prevention (CDC). This review covers the discovery and challenges in the development of therapeutic countermeasures against select microorganisms and toxins from these categories. We also cover existing antibiotic treatments, and early detection and diagnostic strategies for intervening against these biothreat agents at a point in disease progression when the prognosis can still be influenced; and to guide the selection of the optimum therapeutic protocols. Furthermore, although a detailed review of vaccines for biothreat agents exceeds the scope of this manuscript, an important point to consider is that the described therapeutics will most likely be used in combination with vaccines, which possess the advantage of providing long-term immuno-protection.

*Developmental Therapeutics Program, Target Structure-Based Drug Discovery Group, National Cancer Institute-SAIC, Frederick, Maryland 21702, USA.

†United States Army Medical Research Institute of Infectious Diseases, Frederick, Maryland 21702, USA.

Correspondence to S.B.
e-mail:
sina.bavari@amedd.army.mil/bavaris@ncicrf.gov
doi:10.1038/nrd1694

Countering biological toxins

Research to identify/develop therapeutics against biological toxins falls into two categories: relatively large biological inhibitors, such as antibodies and decoy proteins; and small-molecule inhibitors (both peptidic and non-peptidic). The identification and development of therapeutics against anthrax toxin, botulinum neurotoxins, ricin toxin and staphylococcal enterotoxins are discussed. This section is limited mainly to

small-molecule inhibitors, and a brief review of antibody development and design against biotoxins is mentioned in TABLE 1.

Anthrax toxin. The toxin secreted by *BACILLUS ANTHRACIS*, ANTHRAX TOXIN (ATX), possesses the ability to impair innate and adaptive immune responses^{1–3}, which in turn potentiates the bacterial infection. This suggests that inhibiting ATX activity is a viable therapeutic modality—blocking the actions of this toxin should provide the window of opportunity that is necessary for conventional antibiotics, in combination with the inherent immune response, to clear the bacterium well before deadly sepsis and toxic shock occur. FIGURE 1 shows how lethal toxin (LT, which comprises protective antigen (PA) + lethal factor (LF)), attacks cells. The potency of LT is shown in TABLE 2.

The action of ATX can be inhibited in several ways. One method would be to interfere with the furin-mediated cleavage of PA to its active form (PA₆₃) following host-cell receptor binding^{4–7}. To this end, hexa-D-arginine has been identified⁸, and has demonstrated the capacity to delay ATX toxæmia *in vivo*⁹. Following this approach, a more potent nona-D-arginine has been generated¹⁰.

Non-functional (decoy) PA mutants that co-assemble with wild-type PA, and interfere with LF/oedema factor (EF) transport into the host-cell cytosol, have shown

| Report Documentation Page | | | Form Approved OMB No. 0704-0188 | |
|---|------------------------------------|-------------------------------------|---|----------------------------------|
| <p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> | | | | |
| 1. REPORT DATE 1 APR 2005 | 2. REPORT TYPE N/A | 3. DATES COVERED - | | |
| 4. TITLE AND SUBTITLE The evolving field of biodefense: therapeutic developments and diagnostics, Nature Review Drug Discovery 4:281-287 | | | 5a. CONTRACT NUMBER | |
| | | | 5b. GRANT NUMBER | |
| | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) Burnett, JC Henchal, EA Schmaljohn, AL Bavari, S | | | 5d. PROJECT NUMBER | |
| | | | 5e. TASK NUMBER | |
| | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) United States Army Medical Research Institute of Infectious Diseases, Fort Detrick, MD | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| | | | 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited | |
| 13. SUPPLEMENTARY NOTES The original document contains color images. | | | | |
| 14. ABSTRACT The threat of bioterrorism and the potential use of biological weapons against both military and civilian populations have become major concerns for governments around the world. For perspective, in 2001, anthrax-tainted letters sent through the United States Postal Service resulted in several deaths, caused widespread public panic, and incurred a heavy economic toll. If such a small-scale act of bioterrorism could have such a huge impact, then the affects of a large-scale attack would be catastrophic. This review covers recent progress in developing therapeutic countermeasures against, and diagnostics for, such agents. | | | | |
| 15. SUBJECT TERMS biodefense, biothreats, diagnostics, review | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT SAR | 18. NUMBER OF PAGES 17 |
| a. REPORT unclassified | b. ABSTRACT unclassified | c. THIS PAGE unclassified | 19a. NAME OF RESPONSIBLE PERSON | |

REVIEWS

ANTHRAX TOXIN
A complex composed of three proteins: protective antigen (PA), lethal factor (LF) and oedema factor (EF).

SNARE COMPLEX
A complex composed of SNAP25, VAMP (also referred to as synaptobrevin) and syntaxin that is involved in membrane fusion and the exocytosis of acetylcholine into neuromuscular junctions.

Table 1 | Antibodies that target biological toxins

| Target | Source | Comments | References |
|-----------------------------|-----------------------------|--|------------|
| Anthrax toxin | Human, humanized and murine | Many have shown protection against both anthrax lethal toxin and <i>Bacillus anthracis</i> . | 180–185 |
| Botulinum neurotoxins | Human, humanized and murine | Antibodies against all seven serotypes are needed. Some have been used in combination; affinity might be crucial for protection. Broad neutralizing antibodies are needed. Most antibodies are against the carboxyl end of the toxin; should explore other sites. | 186–194 |
| Ricin | Avian and murine | Have shown protection <i>in vivo</i> . Critical need for high affinity antibodies. Genetically inactivated ricin can be used as an antigen. Aerosolized ricin induces lung damage even in surviving subjects ²⁰¹ . Adjunctive therapeutics are desired. | 195–202 |
| Staphylococcal enterotoxins | Human, avian and murine | Some have shown protection against aerosolized toxin, need an antibody with broad neutralizing activity against all staphylococcal enterotoxins. | 62,203,204 |

promise^{11,12}. Another method would involve interfering with PA–LF or PA–EF binding events. A polyvalent compound consisting of a polyacrylamide backbone substituted with multiple copies of a peptide (HTSTY-WWLDGAP) provides protection against LF¹³. Finally, identifying or generating molecules that bind within the PA heptamer pore, thereby blocking LF/EF release into the host-cell cytosol, is also a potential avenue for toxin inhibition. In anticipation of such research, Nguyen¹⁴ has generated a structurally viable PA heptamer model that will be useful for future drug discovery.

LF has been recognized as one of the main virulence components of *B. anthracis*. Consequently, there is much interest in identifying inhibitors of this metalloprotease. Several hydroxamate inhibitors of LF have been identified^{15,16}, one of which, In-2-LF¹⁶, has a $K_i = 1.0 \text{ nM}$ *in vitro*. By incorporating a metal-chelating moiety, a potent inhibitor MKARRKKVYP-NHOH ($K_i = 0.0011 \mu\text{M}$) was generated^{17,18}. Using this information, additional peptidic inhibitors were identified¹⁷ (TABLE 3). Panchal *et al.*¹⁹ used a high-throughput assay to analyse the National Cancer Institute's (NCI's) Diversity Set. Several small (non-peptidic) molecules with drug-like properties were identified (TABLE 3; FIG. 2a). Some of these compounds were identified via subsequent three-dimensional database mining. On the basis of compounds identified during this study, a common pharmacophore for LF inhibition was generated that will provide a template for identifying new leads. The search for LF inhibitors has also prompted the application of less conventional technologies — for example, a mass spectrometry-based technique was used to identify the inhibitor DS-998 (TABLE 3)²⁰. Finally, nature has proven once again to be a pharmaceutical treasure chest: natural products, including epigallocatechin-3-gallate ($IC_{50} = 97 \text{ nM}$), an isolate of green tea (TABLE 3)²¹, and aminoglycosides, including neomycin B ($K_i = 7.0 \text{ nM}$)²², are potent LF inhibitors.

Two notable inhibitors of the adenylate cyclase activity of EF were identified during a screen of the Available Chemical Directory database²³ (TABLE 4), whereas an active metabolite of adefovir dipivoxil (TABLE 4) was found to selectively inhibit EF with high affinity²⁴.

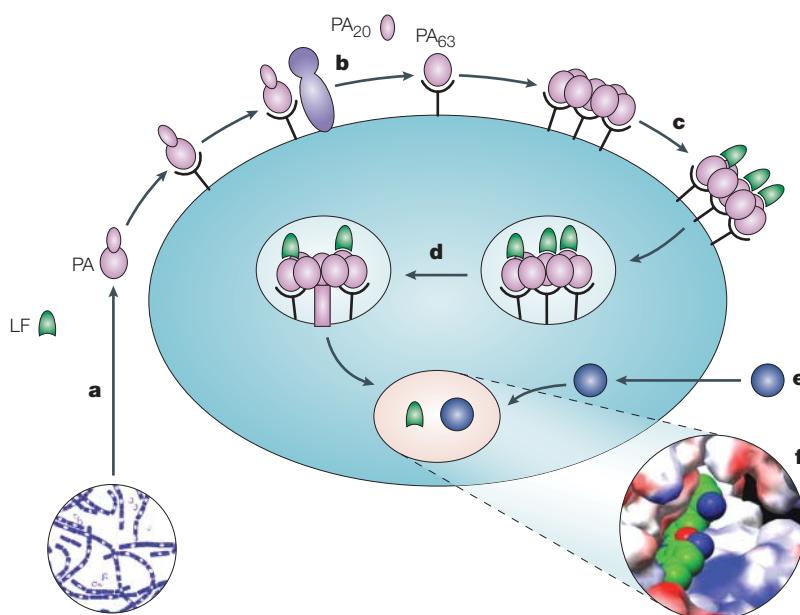


Figure 1 | A schematic of anthrax toxin (ATX) lethal factor cell entry. **a** | ATX is secreted by *Bacillus anthracis*. **b** | The inactive form of protective antigen (PA₆₃) binds to a host-cell receptor, where it is cleaved by a furin-related protease, to give active PA₆₃. **c** | PA₆₃ heptamerizes and can bind to either lethal factor (LF) or oedema factor (EF) (in this depiction the heptamer binds LF). **d** | The complex is endocytosed, and LF (as shown) or EF (not shown) translocates from the endosome into the host-cell cytosol. **e** | Therapeutics, in this example NSC 12155 (REF. 19), are being designed to enter intoxicated cells and inhibit the protease activity of LF. **f** | A surface depiction of NSC 12155 bound within the LF substrate-binding cleft is shown. The inhibitor carbons are green, nitrogens are blue and oxygens are red. The surface of LF is red for acidic surface, blue for basic surface, and white for neutral surface.

Botulinum neurotoxins. Botulinum neurotoxins (BoNTs) are the most potent of the biological toxins (TABLE 2), are easily produced and can be delivered via an aerosol route²⁵. There are seven BoNT serotypes (A–G), and each cleaves a specific component of the soluble *N*-ethylmaleimide-sensitive factor attachment protein receptor SNARE COMPLEX. This cleavage impairs the release of acetylcholine, and can lead to deadly flaccid paralysis. The toxin is composed of a heavy chain

Table 2 | Comparative biological potency of biodefence toxins

| Toxin | LD ₅₀ (μg per kg) | Source |
|------------------------------|--------------------------------|-----------------------------------|
| Botulinum toxin A | 0.001 | Bacterium |
| Tetanus toxin | 0.002 | Bacterium |
| Shiga toxin | 0.002 | Bacterium |
| Staphylococcal enterotoxin B | 0.02* | Bacterium |
| Diphtheria toxin | 0.1 | Bacterium |
| Maitotoxin | 0.1 | Marine dinoflagellate |
| Ciguatoxin (P-CTX-1) | 0.2 0.7 | Marine dinoflagellate abrin plant |
| Batrachotoxin | 2 | Poison arrow frog |
| Ricin | 3 | Plant |
| Tetrodotoxin | 8 | Pufferfish |
| Saxitoxin | 10 | Marine dinoflagellate |
| Staphylococcal enterotoxin B | 10 (aerosol nonhuman primates) | Bacterium |
| Anthrax lethal toxin | 50 [‡] | Bacterium |
| Microcystin | 50 | Blue-green algae |
| Aconitine | 100 | Plant |
| T-2 toxin | 1,200 | Fungus |

*Predicted human aerosol. [‡]Based on rat model of anthrax PA and LF toxicity. REF. 25 provides an excellent review on inhaled biological toxins. Table adapted from REF. 206.

molecular docking using LCs obtained from available X-ray crystal structures^{42,43}, a pharmacophore for BoNT/A LC inhibition was generated⁴¹ that will be of value for ongoing drug discovery. Furthermore, Breidenbach and Brunger⁴⁴ have recently solved the X-ray co-crystal structure of BoNT/A LC complexed with residues 141–204 of synaptosomal-associated protein 25 (SNAP25). This important structure reveals substrate-recognition exosites that could be exploited for inhibitor design. Toosendanin⁴⁵, a triterpenoid natural product, might act at such an exosite.

The majority of compounds that inhibit BoNT/B metalloprotease activity are pseudo-peptidic in nature. However, two non-peptidic inhibitors have been described^{46,47} (TABLE 6). With regard to pseudo-peptides, phosphoramidon and three of its synthetic derivatives were found to be weak inhibitors⁴⁸, whereas buforin I has also shown activity against the BoNT/B LC⁴⁹. Recently, a Cys-containing peptide inhibitor was also reported⁵⁰. The most effective pseudo-peptide BoNT/B LC inhibitors to date were identified during the course of several complementary studies. Initially, a series of pseudo-tripeptides with nominal K_i values were generated⁵¹. In subsequent publications^{52,53}, side-chain modifications produced more potent inhibitors (TABLE 6)⁵³. In the latest study, the pseudo-tripeptide inhibitors were subjected to minor structural changes, and several compounds with K_i values ranging from 2.3 nM to 5.4 nM were generated, with a symmetrical disulphide derivative displaying the greatest potency (TABLE 6)⁵⁴.

With regard to the BoNT serotype F LC, Schmidt and Stafford recently generated a potent peptidic inhibitor composed of VAMP residues 22–58 (J. J. Schmidt and R. G. Stafford, personal communication).

Ricin toxin. The potency of RICIN TOXIN is shown in TABLE 2. In preparation for inhibitor development, Monzingo and Robertus⁵⁵ solved co-crystal structures of two substrate analogues — formycin monophosphate (FMP) and dinucleotide ApG — bound to the ricin toxin A chain (RTA). Using the FMP-RTA co-crystal as a guide, Yan *et al.*⁵⁶ identified the pterin-based inhibitors pteroc acid and neopterin (TABLE 7). Both inhibitors were co-crystallized with RTA (FIG. 2c). In a follow-up study⁵⁷, an oxazole-pyrimidine ring system (9OG) (TABLE 7) was also found to inhibit the RTA. Aptamers (nucleic-acid ligand⁵⁸) that inhibit the RTA have also been generated. Hesselberth *et al.*⁵⁹ identified a 31-nucleotide aptamer, whereas Tanaka *et al.*⁶⁰, using a mechanistic approach⁶¹, generated a variety of much smaller aptamers containing unnatural sugar and purine derivatives (TABLE 7)⁶⁰.

Staphylococcal enterotoxins. STAPHYLOCOCCAL ENTEROTOXINS (SEs) stimulate a powerful cytokine and immune response, which has earned them the name superantigens (SAGs). FIGURE 2d shows the co-crystal of a SAG and a human class II major histocompatibility complex (MHC) molecule. SEs and other related exotoxins have been implicated in various disorders and

RICIN TOXIN
Isolated from seeds of the castor plant (*Ricinus communis*), ricin toxin consists of a 32-kDa B chain that is linked by a disulphide bridge to a 32-kDa A chain (RTA)^{175,176}. The B chain binds cell surfaces. Once inside the cell cytoplasm, RTA is released, and irreversibly depurinates the 28S rRNA, destroying the elongation-factor-binding site, and thereby disabling cellular protein synthesis^{177,178,179}.

STAPHYLOCOCCAL ENTEROTOXINS
A large group of protein toxins that engage both major histocompatibility complex class II molecules on the surface of antigen-presenting cells and the variable (V) β-chain of a large subset of T-cell receptors.

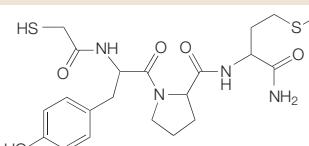
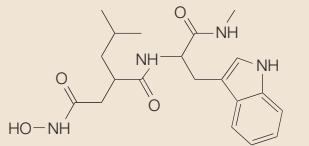
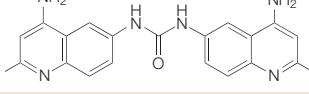
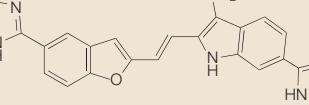
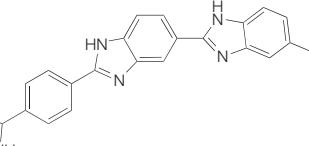
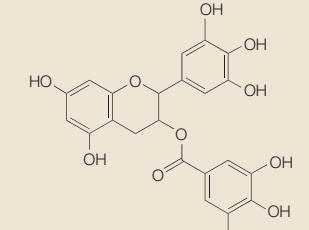
REVIEWS

lethal shock syndrome⁶². Many of these exotoxins are relatively easy to produce in large quantities and are remarkably stable. When delivered by aerosol, these agents are highly incapacitating and lethal. Modulating cytokine responses is one of the clear mechanisms to interfere with SE toxicities^{63,64}.

Soluble decoy receptor, high-affinity variants of the T-cell receptor (TCR) V β region have been engineered to counteract SEs as therapeutic leads^{65,66}. Additional studies have now generated V β proteins against several toxins with picomolar affinities (R. Buonpane and D. Kranz, personal communication). Such high affinity might be essential for neutralizing agents such as SAGs, which are highly toxic even at extremely low concentrations.

Although consensus peptides as therapeutics are presently controversial, in some animal models these mimetic peptides have been shown to diminish the toxicity of SAGs⁶⁷⁻⁶⁹. In one such study, Arad and colleagues⁷⁰ used a mimetic peptide and produced evidence that divergent SAGs inhibited gene expression of human T_H1 cytokines. In low molar excess over SAg challenge concentration, this peptide mimetic protected mice from the lethal effects of a broad spectrum of these toxins, even when given post-challenge. The peptide is a mimetic of a domain that is structurally conserved among SAGs, yet it is remote from binding sites for MHC class II and TCR. It has been proposed that SAGs might use this domain to bind to a novel receptor that is crucial for their action (Kaempfer R, personal communication).

Table 3 | Lethal factor (LF) inhibitors

| LF inhibitor chemical structure | Name | In vitro activity | Cell-based assay | References |
|---|----------------------------|---------------------------|--|------------|
|  | 2-thiolacetyl-YPM-amide | $K_i = 11 \mu\text{M}$ | | 17 |
|  | GM6001 | $K_i = 2.1 \mu\text{M}$ | 100 μM concentration protects cells. | 17 |
|  | NSC 12155 | $K_i = 500 \text{ nM}$ | | 19 |
|  | NSC 357756 | $K_i = 4.9 \mu\text{M}$ | 100 μM concentration protects cells. | 19 |
|  | NSC 369721 | $K_i = 4.2 \mu\text{M}$ | | 19 |
|  | Epigallocatechin-3-Gallate | $EC_{50} = 97 \text{ nM}$ | 10 μM protects cells. | 21 |
|  | DS-998 | $K_i = 1.1 \mu\text{M}$ | 1–10 μM concentration protects cells. | 20 |

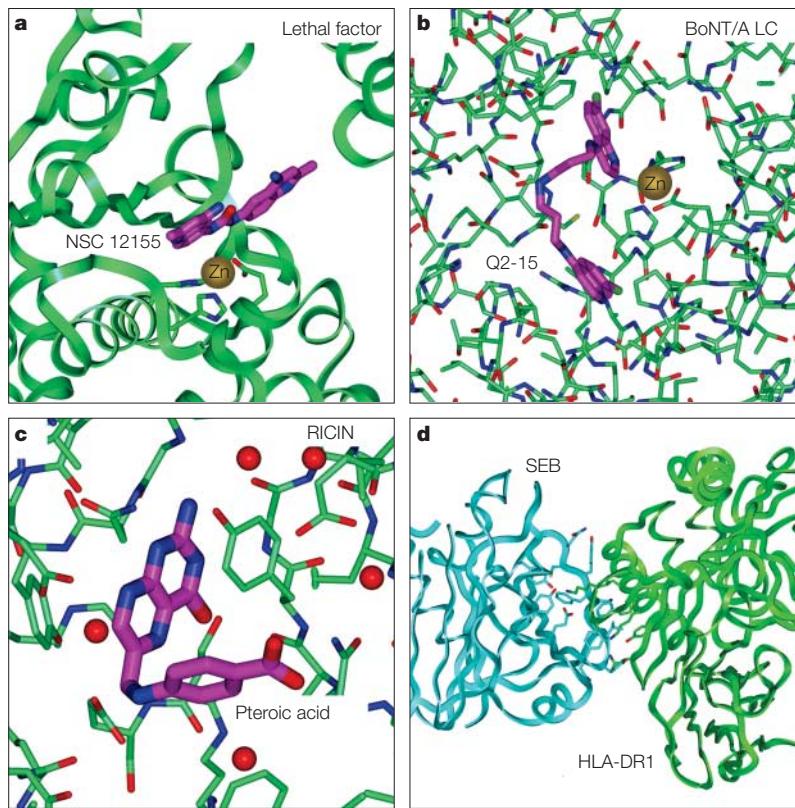


Figure 2 | Toxin interactions with inhibitors (a–c) or other proteins (d). **a** | The co-crystal structure of NSC 12155 bound in the lethal factor (LF) substrate-binding cleft (PDB Ref Code = 1PWP). LF is shown in green ribbon. Residues of the LF catalytic engine are shown in stick. Carbon atoms are green; oxygen atoms are red; and nitrogen atoms are blue. NSC 12155 carbons are magenta. The inhibitor sits in close proximity to the enzyme's catalytic zinc (gold). **b** | Inhibitor Q2-15 docked in the botulinum neurotoxin serotype A (BoNT/A) light-chain (LC) substrate-binding cleft. The BoNT/A LC model is a dynamics conformation²⁰⁵ generated from the X-ray crystal structure of PDB ref code = 1E1H. Colours are as described for **a**. Additionally, enzyme residues are rendered in stick. Q2-15 carbons are magenta; and Q2-15 chloro substituents are light green. One of the 7-chloro-quinoline components interacts with the catalytic zinc of the enzyme, whereas the other binds in a pocket located behind the catalytic engine of the enzyme. **c** | The co-crystal structure of pteroic acid bound in the substrate-binding pocket of the ricin A chain (PDB Ref Code = 1BR6). Colours are as described for **a** and **b**. Red spheres are water molecules. **d** | The co-crystal structure of the SEB–HLA-DR1 interaction (PDB Ref Code = 1SEB). SEB is depicted as cyan ribbons and HLA-DR1 is depicted as green ribbons. The side chains of residues spanning the contact interface are shown in stick, with carbon colours corresponding to protein ribbon colour. Residue oxygens are red and nitrogens are blue.

Targeting viral pathogens: variola and filoviruses

Therapeutics for viral infections can be broadly categorized as agents that attack the virus and its replicative cycle directly, or as agents that assist and fortify host immune defences. In principle, there are abundant targets and numerous strategies for both categories. TABLE 8 provides an overview of the strategies and opportunities available for new therapies against a virus, juxtaposed with some of the challenges in bringing such strategies into clinical use. The view presented is necessarily incomplete, but serves to highlight both the apparent vulnerabilities of viruses and the extraordinary challenges inherent to dampening logarithmic viral replication to a medically significant degree. As reviewed recently by De Clercq⁷¹, there are only 37 licensed antiviral drugs (not including interferons or

antibodies) available for clinical use. Many are for the treatment of HIV, 12 are for treating herpes virus (herpes simplex virus (HSV), Varicella–Zoster virus (VZV) and cytomegalovirus (CMV)) and 4 are for the therapy and prophylaxis of influenza virus. However, a cause for optimism is that the viruses of greatest concern in biowarfare and bioterrorism cause acute viral infections, which for lucky survivors is followed by immune recovery. Antiviral therapies therefore need only be effective for relatively short periods (see BOX 1 for case examples of filoviruses and orthopoxviruses).

Antiviral drugs. Attachment and entry remain enigmas for both filoviruses and orthopoxviruses, and emerging data are mired in uncertainty and controversy. The search for specific filovirus receptors^{72,73} has been countered by evidence of more ubiquitous and unspecific lectin-like receptors^{74,75} that might be difficult to antagonize with drugs. However, recent structure–activity relationship (SAR) studies indicate that Cyanovirin-N, a carbohydrate-binding protein, might inhibit Ebola virus entry⁷⁶. Orthopoxviruses, though very different in their surfaces from the sugary filaments of Ebola and Marburg, are similarly the subject of viral attachment and entry research⁷⁷. Fusion inhibition, which has proven fruitful for treating both HIV and influenza⁷¹, could provide therapeutic opportunities for both viral genera, and is being actively pursued^{77–80}. Inhibition of viral replication seems to be especially feasible for both filoviruses and orthopoxviruses: numerous genomes have been sequenced, several key enzymes identified, basic replicative steps described and structural associations among proteins partially described^{77,81}.

This abundance of potential targets could result in several therapeutic approaches, including antisense targeting of the viral genome, inhibition of the replicase or polymerase activity by small-molecule inhibitors, as well as other specific molecular targets essential for the formation of a replication-competent complex⁸². The recent development of reverse genetics and filovirus reporter-based mini-genomes⁸³, as well as green fluorescent protein (GFP)-expressing Ebola virus⁸⁴, is expected to significantly facilitate the identification of inhibitors of filovirus replication. Final assembly and viral egress from cells is simpler for filoviruses than for poxviruses. Results from electron microscopy have long indicated that the final assembly of filamentous Ebola and Marburg viruses occurs at cell membranes^{85,86}, and recent work has shown that filoviruses are among the subset of viruses that exploit specialized cell-membrane regions called lipid rafts⁸⁷. Filovirus raft assembly might therefore be a viable target. Reverse genetics experiments can be used to explore whether a putative target, such as furin cleavage site of Ebola virus, is essential for viral infection⁸⁸. Compared with filoviruses, poxvirus egress from cells is considerably more complicated⁷⁷, a situation that would seem to make the target even more vulnerable. Over the years, vaccinia virus mutants defective in various aspects of final assembly have been identified, host proteins implicated and

REVIEWS

Table 4 | **Oedema factor (EF) inhibitors**

| EF inhibitor chemical structure | Name | In vitro activity | Cell-based assay | References |
|---------------------------------|--------------------|---|--|------------|
| | 119804 | $IC_{50} = 60 \mu M$ | 125 μM and greater prevents cAMP-induced cell rounding. | 23 |
| | 277890 | $IC_{50} = 90 \mu M$ | 125 μM and greater prevents cAMP-induced cell rounding. | 23 |
| | Adefovir dipivoxil | $K_i = 27 \text{ nM}$ (for adefovir diphosphate, active cellular metabolite of adefovir dipivoxil) | $IC_{50} = 0.1\text{--}0.5 \mu M$ | 24 |

compounds identified that inhibit late particle formation. Additionally, the apparently effective but problematic antiviral drug cidofovir seems to be effective against many orthopoxviruses, and is potentially useful for the treatment of smallpox and vaccinia^{71,89}.

Adjunctive therapy. Filovirus infections are associated with a number of pathological conditions, including disseminated intravascular coagulation, which has been proposed to result from upregulation of tissue factor on the surface of leukocytes⁹⁰. Partial success against Ebola virus infections in rhesus monkeys using recombinant nematode anticoagulant protein C2 has recently been reported⁹¹. Although this study is encouraging, the utility of anticoagulant therapy in humans requires further studies — in particular in combination with specific antiviral therapeutics.

Therapeutic antibodies. Both filoviruses and orthopoxviruses illustrate how the potential complexity and effectiveness of antibody-mediated protection is so often underestimated. Viral neutralization — commonly interpreted to mean the capacity of an immunoglobulin to interfere with viral attachment or entry — is only part of the protective role of antibodies⁹², and is sometimes insufficient.

In rodent models of lethal Ebola and Marburg viruses, the administration of both polyclonal and monoclonal antibodies unambiguously confers protection before and sometimes after viral infection, and the demonstration of virus-neutralizing activity in the transferred antibody is a poor predictor of its efficacy *in vivo*^{93–96}. The few antibodies tested in sensitive non-human primate models of filovirus infection have delayed viraemia and death, but have not been fully preventative when the viral challenge was robust⁹⁷. This has led to premature assertions about the irrelevancy of antibodies as filovirus therapies. Lessons from viral vaccine studies with Ebola and Marburg viruses repeatedly show

that antibodies to the viral glycoprotein in conjunction with T-cell responses to this and other proteins are required for optimal protection^{94,98–102}. Attempts to influence clinical outcomes in humans by the transfer of plasma from convalescent to ill individuals produced encouraging results^{103,104}, but these studies were inadequately controlled and therefore inconclusive.

A common observation in orthopoxviruses is the production of neutralizing antibodies (raised against inactivated virus) that alone prove insufficient to prevent disease and death, but which are protective when combined with an additional antibody population (found in serum from animals that had been infected with live virus)¹⁰⁵. We repeated this observation both with monoclonal antibodies¹⁰⁶ and with DNA vaccines that evoked antibodies^{106,107}; in this case, even the most potent neutralizing antibodies (against the vaccinia virus protein L1R) were insufficient to prevent the inexorable spread of virus in infected animals. In contrast, an antibody to a virally encoded cell-surface protein (A33R) was sufficient by itself or in conjunction with anti-L1R to provide robust protection from vaccinia virus in rodents. Others, extending the observations to additional proteins, have reported similar findings¹⁰⁸, and an experimental DNA vaccine against monkeypox virus in non-human primates yielded concordant results¹⁰⁷. This raises a question: how might antibodies, in addition to neutralizing antibodies, confer a therapeutic effect? Early observations^{92,109} implicated the capacity of antibodies to bind to viral proteins on the surface of infected cells, and subsequent observations, including those with filoviruses and orthopoxviruses, tend to be consistent with the proposed requirement that the targets of non-neutralizing antibodies be externally exposed. Mechanistically, one might evoke complement-mediated lysis of cells, antibody-dependent cellular cytotoxicity (in which Fc receptor-bearing cells destroy virally infected cells), perturbation of late events in viral assembly (as in the drug targeting above) or, as

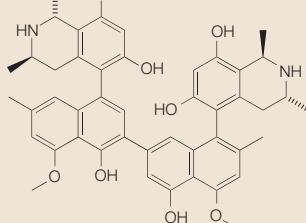
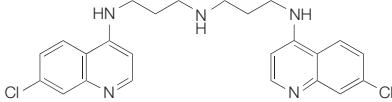
in the case of orthopoxviruses, the targeting of a particularly important but quantitatively minor viral population^{105,108}. In terms of the therapeutic value of antibodies, complexity is added by the search for antibodies in addition to those that can be assayed rapidly by binding or neutralization. Historically, the potency of vaccinia immune globulin (licensed for the treatment of smallpox vaccine complications) was judged by its neutralization capacity, a strategy salvaged by the acquisition of antibodies from donors whose sera also contained many other antibodies as well¹¹⁰.

Augmenting or protecting innate immunity. The goal of some antiviral agents is to tip the balance of the immune response towards innate immunity and allow specific immune clearance mechanisms (adaptive immunity) to take over¹¹¹. At the crossroads of many innate immune responses are interferons, a family of molecules that can directly evoke antiviral responses. However, the utility of interferons as broad-spectrum antivirals has been limited both by the transience and the toxicity of their effects. This has engendered caution about the prospects for a broad array of other newly described cytokines that also stimulate innate immunity. On the other hand, other opportunities for drug intervention have arisen in targeting viral pathogens. The identification of proteins produced by vaccinia and influenza virus that act as interferon antagonists^{112,113} was followed by the demonstration that Ebola¹¹⁴ and Marburg¹¹⁵ viruses also make interferon antagonists. Additionally, orthopoxviruses synthesize an impressive array of homologues of cytokines, cytokine receptors, complement proteins, growth hormones and other molecules — the effects of which could confound innate immune responses¹¹⁶. Our ability to modify the innate immune response in a therapeutically significant manner necessitates a deeper understanding of the role of the components of this arm of the immune system in specific viral infections.

Recently, a crucial role for natural killer (NK) cells was defined in protection against Ebola infection¹¹⁷. Interestingly, adoptive transfer of NK cells treated with Ebola virus-like particles and not inactivated Ebola virus resulted in significant protection of mice against lethal challenge, indicating that mobilizing the effector innate response early in infection might be a promising therapeutic strategy against filoviruses.

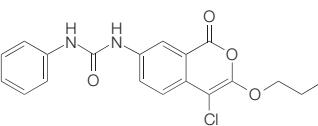
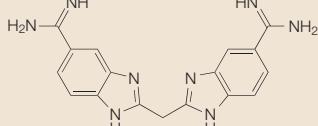
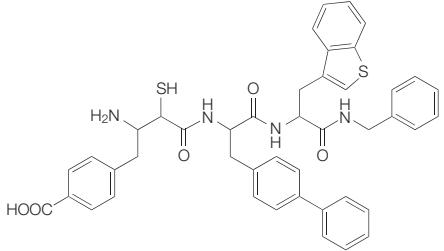
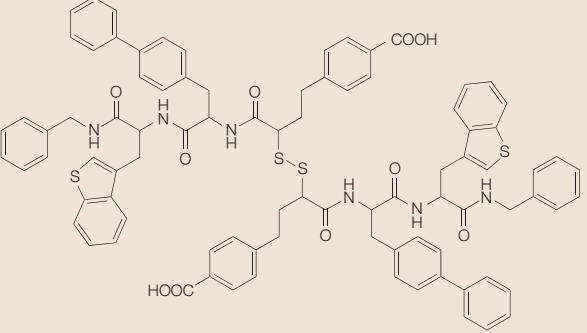
Targeting host pathways. Viral pathogens have evolved over millennia by adapting to a limited number of cellular mechanisms for cellular entry, replication, assembly and budding. Although a tremendous amount of effort has been devoted in the past decades to the development of therapeutic strategies targeting virus components, half of this work involves a single virus (HIV). In contrast, the common cellular pathways used by a wide array of viruses have been largely neglected as therapeutic targets. In this regard, genetically engineered microbes represent major challenges for biodefence both because the pathogenicity of the organism might be unrecognized and/or the pathogenicity might be tailored to counter existing pathogen-targeted therapeutics. Host-targeted therapeutics would be the most viable option in coping with such unpredictable challenges. Such host-targeted therapeutics would have two advantages: they would act as broad-spectrum therapeutics and block all of the viruses that use the affected pathway; and they would make it more difficult for the pathogen to develop resistance, because there would be few alternative cellular pathways available for the virus to take advantage of. Besides cellular receptors and co-factors, a number of intracellular pathways, such as the vacuolar protein-sorting machinery¹¹⁸, cytoskeletal network¹¹⁹ and components of cellular antiviral defence^{120,121}, have been identified as crucial for viral pathogenesis. However, despite these advances, our understanding of the host pathways involved in viral pathogenesis remains limited. Genetic approaches such

Table 5 | **Botulinum serotype A light chain (BoNT/A LC) inhibitors**

| BoNT/A LC inhibitor chemical structure | Name | In vitro activity | References |
|---|--|--------------------------------------|------------|
|  | 2-mercaptop-3-phenylpropionyl-RATKML-amide | $K_i = 330$ nM | 36 |
|  | Michellamine B | 62% inhibition, 20 μM concentration. | 41 |
|  | Q2-15 | 60% inhibition, 20 μM concentration. | 41 |

REVIEWS

Table 6 | **Botulinum serotype B light chain (BoNT/B LC) inhibitors**

| BoNT/B LC inhibitor chemical structure | Name | In vitro activity | References |
|--|---|------------------------|------------|
|  | ICD-1578 | $IC_{50} = 27 \mu M$ | 46 |
|  | BABIM | $IC_{50} = 5-10 \mu M$ | 47 |
|  | Biphenyl/benzothiophenylmethyl derivative | $K_i = 20 \text{ nM}$ | 52 |
|  | Bis-derivative | $K_i = 2.3 \text{ nM}$ | 54 |

as RNA interference (RNAi), as well as various physical and functional knockout technologies, need to be applied to identify host genetic pathways involved in viral pathogenesis and to establish the degree of commonality of these pathways across viral families. Molecular details of these pathways and the nature of their interactions with viral components need to be intensively studied by genetic, biochemical, structural and modelling approaches. This detailed body of knowledge would serve as a basis for identifying host targets and the rational design of broad-spectrum therapeutic strategies.

Existing antimicrobial treatments

At this time there are therapeutic protocols for treating those infected with many of the bacterial biowarfare pathogens. However, the scope of recovery is variable — in the case of individuals infected with inhalational anthrax, there is a limited window of opportunity during which antibiotics will control and eliminate the infection. This section of the review covers characteristics (TABLE 9) and current drug therapies for three biowarfare agents: anthrax, plague and tularemia.

Naturally occurring strains of *B. anthracis* are generally susceptible to penicillins, first-generation

cephalosporins, tetracyclines, rifampin, aminoglycosides, vancomycin, clindamycin and fluoroquinolones. It was recently found that 20 strains of *B. anthracis* also show sensitivity to imipenem, meropenem, daptomycin, quinupristin-dalfopristin, linezolid, GAR936, BMS284756, ABT773, LY333328 and resistance to clofazamine^{122,123}. The CDC and the Working Group for Civilian Biodefense treatment guidelines have been published for treatment of pulmonary anthrax¹²⁴, and are provided in TABLE 10. The choice of the second or third antibiotic should be influenced by the likely resistance pattern of the strain causing the infection, and consideration should be given to antibiotics that penetrate the blood-brain barrier (penicillins and carbapenems, for example) due to the high frequency of meningitis associated with inhalational anthrax exposure¹²⁵. The duration of therapy is controversial, but involves at least 60 days of treatment^{124,125}. Corticosteroids have been mentioned as a possible adjunctive therapy in the setting of meningitis or severe mediastinal oedema¹²⁵, but there are no data to definitively support their use.

A major concern with regard to *B. anthracis* and other microbial biodefence agents is genetically engineered antibiotic resistance. Several reports of recombinant

Table 7 | Ricin toxin chain A (RTA) inhibitors

| RTA inhibitor chemical structure | Name | In vitro activity | References |
|----------------------------------|--------------|----------------------|------------|
| | Neopterin | $K_i = >2$ mM | 56 |
| | Pteroic acid | $K_i = 0.6$ mM | 56 |
| | 9OG | $IC_{50} = 0.4$ mM | 57 |
| | P-14 | $K_i = 0.18$ μ M | 60 |
| | 1N-14 | $K_i = 0.48$ μ M | 60 |

plasmids that confer antibiotic resistance when inserted into *B. anthracis* have been published. One plasmid-containing strain was resistant to tetracycline, doxycycline and minocycline¹²⁶. In another study, a recombinant plasmid encoding for resistance to penicillin, tetracycline, chloramphenicol, rifampin, macrolides and lincomycin was inserted into the *B. anthracis* strain STI-1, which reportedly stably inherited the plasmid over several generations¹²⁷. The possibility of antibiotic resistance in this pathogen indicates the

YERSINIA PESTIS

The causative agent of plague, it is an aerobic, Gram-negative bacillus from the bacterial family Enterobacteriaceae.

Box 1 | Case examples of filoviruses and orthopoxviruses

The filoviruses (Ebola and Marburg viruses) and the orthopoxviruses (variola/smallpox, monkeypox and other pox viruses) are high-priority viral threats, and there is an acute need for therapeutics that target these pathogens. Ebola and Marburg viruses are exceptionally deadly (70–90% mortality in some outbreaks), but are relatively simple viruses, consisting of seven genes encoded in a single strand of RNA¹⁵⁹. They are moderately contagious, but otherwise have numerous characteristics commonly associated with biological weapons¹⁶⁰. These viruses are endemic in Africa^{161,162} and, despite a great deal of scientific progress in the past 10 years^{81,93,95,96,98,163–165}, no vaccines or treatments are available for clinical use. For comparison, orthopoxviruses are large DNA viruses that have nearly 200 genes and some of the most complex viral replication cycles known. Variola virus, which causes smallpox, is the most feared of this genus¹⁶⁶ because it is highly contagious, incapacitating, disfiguring and potentially deadly (historical highs of around 40% mortality in unvaccinated persons). Monkeypox, a rodent virus endemic in Africa, is far less contagious than variola but in some outbreaks has caused up to 10% mortality in unvaccinated individuals. The classical smallpox vaccine, which consists of vaccinia virus, affords relatively robust protection against both variola and monkeypox viruses, but has proven problematic in the modern era not only because of previously known adverse reactions (including disseminated vaccinia), but because of a rediscovered association with myocarditis^{167,168}. However, safer vaccines are in the research pipeline^{107,169}. Vaccinia immune globulin, an antibody-containing product from vaccinated persons, was licensed and is now offered under investigational status for the treatment of disseminated vaccinia⁸⁹.

importance of initial combination therapy when exposure to a genetically modified strain is suspected.

YERSINIA PESTIS is typically susceptible *in vitro* to penicillins, many cephalosporins, imipenem, meropenem, aminoglycosides, amikacin, quinolones and tetracyclines. It is variably susceptible to trimethoprim, chloramphenicol and rifampin, and is commonly resistant to macrolides, clindamycin, novobiocin, quinupristin-dalfopristin and clofazamine (H. Heine, personal communication). (See TABLE 10 for recommended antibiotic treatments for pneumonic plague.) The preferred therapy for *Y. pestis* infection is an aminoglycoside, with streptomycin as an FDA-approved medication and gentamicin often mentioned as an alternate antibiotic.

Although rarely reported, naturally occurring, highly antibiotic-resistant strains of *Y. pestis* do occur. In a recent report, a strain isolated from a boy in Madagascar was demonstrated to have acquired a plasmid that mediated resistance not only to streptomycin, chloramphenicol and tetracycline, but also to ampicillin, sulphonamides, kanamycin, spectinomycin and minocycline. These naturally occurring, highly resistant antibiotic strains are extremely concerning with respect to the development of biological weapons.

FRANCESSELLA TULARENSIS is generally susceptible *in vitro* to aminoglycosides, tetracyclines, rifampin and chloramphenicol^{128–133}; however, many strains seem to be resistant to β -lactam and monobactam antibiotics¹³³. (See TABLE 10 for recommended tularemia treatments.) Similarly to the treatment of plague, streptomycin or gentamicin are the preferred therapy when there are no contraindications to the use of these medications^{134,135}. Ciprofloxacin was effective in treating a recent tularemia outbreak in Spain¹³⁶.

Rapid detection and diagnostics

The early detection and diagnosis of infection or intoxication with biological select agent and toxin (BSAT) is essential if intervention is to occur at a point at which the prognosis can still be influenced, and also to guide the selection of the optimum therapeutic protocol (TABLE 10). In addition, such information can greatly facilitate the logistics of mobilizing supplies and personnel to areas of exposure. Here, 'detection' is defined as including those technologies required to identify a biological threat in the environment before or coincident with exposure. Environmental detection usually involves the testing of air, soil, fomites, water and foodstuffs. 'Laboratory diagnosis' includes those methods used to confirm the clinical observations of a physician by evaluation of standard clinical specimens, such as blood, serum, exudates, saliva, stool and tissues (TABLE 9). The necessity for the rapid detection of BSAT-related illness and intervention with optimal therapeutic protocols was well illustrated during the 2001 anthrax attacks (BOX 2).

Challenges facing the National Laboratory Response Network. In 1999 a national laboratory response network (LRN) for bioterrorism was established by the CDC to test for biological and chemical agents (see FIG. 3

REVIEWS

Table 8 | Quenching viral replication: opportunities and challenges

| Viral event | Dynamic consequences | Opportunities | Challenges |
|---|--|--|---|
| Virus (free or extracellular) | Gradual inactivation in a cell-free environment. | Specific binding and harmless removal of virus — for example by antibodies, heteropolymers and small molecules. Specific binding by drug or antibody to destabilize or irreversibly stabilize coat. | Phenotypic variation of viral population (quasi-species). Possibility of enhancing uptake and therefore disease. Natural diversity of coats among viral species and strains. |
| Attachment to cells | Binding of virus to receptor(s) or unspecific ligands. Earliest signalling of innate immunity. | Receptor blockade by antibodies or other drugs. Deliberate prior activation of innate immunity. | Genotypic and phenotypic variation present in an amplifying virus population and escape mutants. Redundancy and degeneracy in viral and cell receptors. Adverse and transient effects of activating innate immunity. |
| Entry, fusion, release of viral genome, translocation | Penetration and unveiling of RNA or DNA, sometimes stepwise or compartmentalized. Early defence cascades activated, including interferons, RNAi, apoptosis. | Binding to fusion domain, fusion inhibition. Targeting exposed RNA, DNA, for example, nuclease, antisense. | Fusion domains often cryptic, and are only transiently accessible. Nucleic acids protected by viral proteins, compartmentalization. |
| Complex cycle of transcription, translation and genome replication | Cell defence cascades are amplified; viral antagonists of intra- and extracellular defences produced; viral proteins on cell surfaces expressed; viral proteins secreted; MHC- associated viral peptides processed; perturb 'normal' cell surface. | Specifically bind/disrupt viral protein/nucleic-acid functions and interactions (for example, protease inhibitors and replicase inhibitors); competitively inhibit viral antagonists of innate and adaptive immunity; specifically target viral proteins on cell surfaces (for example, antibodies for ADCC or targeted toxin); exploit, amplify and influence the innate and adaptive responses (for example, NK cells and CTL) to eliminate 'modified self'. | Delivery of active compounds to intracellular targets; identification of appropriate targets; escape mutants; variation among viral strains; insufficient knowledge of how to safely manipulate the immune system without exacerbation of disease and autoimmunity in some individuals. |
| Pre-assembly: an orchestrated, compartmentalized encapsidation of nucleic acid with viral proteins | Specific or quasi-specific associations between viral proteins and nucleic acids. | Identify and inhibit protein–protein interactions; perturb nucleic-acid encapsidation motifs (for example, using a drug antagonist or antisense). | Delivery of active compounds to intracellular targets; identification of appropriate targets. |
| Final assembly: can involve translocation, acquisition of outer capsid and/or budding from cell membranes | Self-assembly driven by specific binding and movement of proteins; preferential assembly in specialized proteins (for example, lipid rafts); exploitation of cellular proteins and pathways (for example, TSG101); cell exhaustion and apoptosis; and death. | Bind and disrupt proteins involved in final packaging; reversibly perturb essential cellular sites and proteins. | Delivery of active compounds to intracellular targets; identification of appropriate targets; overall safety of compounds that disrupt cellular processes. |
| Repetition <i>in vivo</i> , manifested by tissue tropisms, damage and disease | Logarithmic amplification of viral burden; fatal virus- induced lesions in crucial organs; triggering of 'cytokine storms'; immunopathology from potent but lagging response. | Treat symptoms to sustain victim until immune system prevails; manage immune response and cytokine polarity. | Discovery of active compounds; addressing issues of drug or antibody pharmacokinetics, bioavailability, efficacy, feasibility and safety. |

for a schematic of the process) that could be used during a terrorism incident^{137,138}. Each laboratory in the LRN follows the same rules for sample collection, shipping, agent containment and testing. LRN laboratories maintain secure communication channels among themselves, state and local health authorities, CDC and other federal agencies. The mission of the LRN is to maintain a laboratory network that will quickly respond to acts of biological and chemical terrorism. The system is now organized into a collection of surveillance (previously known as level A), confirmatory (level B and C) and national laboratories (level D).

FDA-approved assays do not exist for most BSAT. The CDC therefore provides LRN-registered clinical laboratories, which are the front-line laboratory responders to biological terrorism, with approved protocols for most of the category A agents and some category B agents. LRN protocols use an integrated

system of well-established microbiological methods, PCR gene amplification and improved immunodiagnostic assays¹³⁹. CDC-supplied reagents and standards exist for the identification of *B. anthracis*, BoNT/A, *Y. pestis*, *F. tularensis* and *Brucella spp*. For a large number of agents, specimens must be sent directly to the CDC in Atlanta, Georgia, USA, or to designated LRN reference laboratories because of the extreme hazard they represent to clinical laboratory personnel and the technical complexity of the analysis required. In most cases the LRN system requires a combination of a screening evaluation at the level of the local hospital clinical laboratory and confirmation by a hierarchical reference laboratory in the system. TABLE 10 shows the estimated time required for conducting LRN protocols, assuming a low-complexity sample or specimen. We can expect that the time required for laboratory confirmation will be worse for samples that must be transported to the

FRANCESSELLA TULARENSIS

The causative agent of tularemia, it is a small, aerobic Gram-negative coccobacilli. This agent is the most infectious human pathogen known. In the past, both the former Soviet Union and the US had programmes to develop weapons containing this bacterium.

Table 9 | Characteristics of selected BSAT

| BSAT | Biological characteristics | Clinical specimens | Diagnostic methods* |
|----------------------|--|---|--|
| Anthrax | Gram-positive rod; spore-forming; aerobic; non-motile; catalase positive; large, grey-white to white, non-haemolytic colonies on sheep-blood agar plates. | Blood; cerebral spinal fluid; pleural effusion fluid; skin-lesion material such as vesicular fluid or eschar. | Culture; γ -phage sensitivity; immunohistochemistry; PCR. |
| Botulism | Gram-positive rod; spore-forming; obligate Anaerobe; catalase negative; lipase production on egg yolk agar; 150-kDa protein toxin (types A–G); 2 subunits. | Serum; gastric aspirates; stool; respiratory secretions. | Culture; immunoassay; mouse neutralization assay; PCR. |
| Plague | Gram-negative coccobacilli often pleomorphic; non-spore forming; facultative anaerobe; non-motile; beaten copper colonies (MacConkey's agar). | Lymph node smears; aspirates; sputum; blood; cerebral spinal fluid. | Culture; immunofluorescence assay; PCR. |
| Smallpox | Large double-stranded DNA virus; enveloped, brick-shaped morphology; Guarnieri bodies (virus inclusions) under light microscopy. | Throat swabs; induced respiratory secretions; serum; aspirates; tissue scrapings. | Viral culture; PCR; EM; immunohistochemistry; immunoassay. |
| Tularaemia | Extremely small, pleomorphic, Gram-negative Coccobacilli; non-spore forming; facultative intracellular parasite; non-motile; catalase positive; opalescent smooth colonies on cysteine heart agar. | Blood culture; serum; ulcer material; conjunctival exudates; sputum; gastric washes; pharyngeal exudates. | Culture; PCR; immunoassay. |
| Ebola and Marburg | Linear, negative-sense single-stranded RNA virus; enveloped; filamentous or pleomorphic, with extensive branching, or U-shaped, 6-shaped or circular forms; limited cytopathic effect in Vero cells. | Serum; liver; spleen; lymph nodes; kidney; lung; and gonads. | Viral culture; PCR; EM; immunoassay; immunohistochemistry. |
| Viral encephalitides | Linear positive-sense single stranded RNA virus; enveloped, spherical virions with distinct glycoprotein spikes; cytopathic effect in Vero cells. | Throat swabs; serum; cerebrospinal fluid. | Viral culture; PCR; EM; immunoassay; immunohistochemistry. |
| Ricin toxin | 60–65 kDa-protein toxin; two subunits; castor bean origin. | Serum; stool; urine; spleen, lung, kidney. | Immunoassay. |

*Includes screening methods and confirmatory assays supplementing standardized protocols in the US National Laboratory Response Network. BSAT, Biological Select Agent and Toxin.

centrally responding CDC laboratory after screening at the local level, as required for smallpox and haemorrhagic fevers. On the basis of the limited public reports of the 2001 response to anthrax attacks, the calculated median time from first medical visit to laboratory confirmation for suspected cutaneous and inhalation anthrax cases ($n = 22$) was 9 days^{140,141}. In most of the cases, in which an optimal antibiotic set was initiated as the first therapeutic option, the diagnosis depended on the astute observations and the sensitivity of the attending physician to the possibility of anthrax. Although the laboratory response has technically improved since 2001, the reaction to an unknown or a genetically engineered threat could mimic the 2001 experience.

Watching and sensing for biothreat agents. Two federally sponsored programs, BioWatch and BioSense, are in the early stages of implementation and will encourage the recognition of biological threat attacks on a wide scale^{142,143}. The BioWatch Program, which is a collaborative program between the Environmental Protection Agency (EPA), the Department of Homeland Security (DHS), the CDC and local authorities, will provide round-the-clock environmental monitoring for the intentional airborne release of select biological threats. Solid-phase filters and sometimes aqueous concentrates from BioWatch air samplers are evaluated for the presence of pathogens by designated local or

state public-health laboratories using LRN protocols and assays. Similar surveillance systems are planned for post offices, and research has begun to devise systems to protect buildings using 'smart' monitoring systems^{144,145}. Presumably after confirmation of the intentional release of a biological agent, local officials will implement a response plan that might include widespread prophylaxis and treatment in accordance with the public-health threat. The BioSense Program will use epidemiological methods to monitor selected surrogate markers of infectious disease outbreaks, such as emergency room visits, absentee rates at schools and work, pharmacy visits and other indicators. Possible limitations for both BioWatch and Biosense are described in BOX 3.

Traditional immunodetection. The detection of agent-specific antibodies has been a traditional method to confirm clinical diagnoses. Others have demonstrated assays for the rapid detection of anthrax-specific antibodies in patient sera¹⁴⁶. Recently, the FDA approved the use of the first commercial assay that detected anthrax-specific antibodies with high sensitivity and specificity. Although these assays are sensitive for detecting anthrax-specific antibodies in highly immunized individuals and convalescent sera, they might not be effective for identifying patients in the early stages of disease. Among postal workers, who arguably received

REVIEWS

Table 10 | Requirements for rapid diagnosis

| BSAT | CDC category | Incubation period* | Disease duration* | Diagnostic approaches [‡] | Time to diagnosis [‡] | Therapeutic options |
|----------------------|--------------|--------------------|--|------------------------------------|--------------------------------|---|
| Anthrax | A | 1–6 days | Death in 3–5 days (untreated) | Level A Protocol | 18–24 h | Ciprofloxacin, doxycycline, penicillin |
| Botulism | A | 1–5 days | Death in 24–72 h (untreated); 30–60 days w/treatment | Level A Protocol | 3–21 days | Equine & human antitoxin |
| Plague | A | 2–3 days | 1–6 days (usually fatal) | Level A Protocol | 2 days | Tetracycline, doxycycline |
| Smallpox | A | 7–17 days | 4 weeks | Level D Protocol | 24–48 h | Vaccinia vaccine, cidofovir |
| Tularaemia | A | 1–21 days | >2 weeks | Level A Protocol | 3 days | Streptomycin, gentamicin |
| Ebola | A | 4–21 days | 7–16 days (usually fatal) | Level D Protocol | 1–3 days | Supportive care |
| Marburg | A | 9–10 days | 5–14 days (usually fatal) | Level D Protocol | 1–3 days | Supportive care |
| Brucellosis | B | 5–60 days | >8 weeks to >1 year | Level A Protocol | 14–21 days | Doxycycline and rifampin |
| Glanders | B | 10–14 days | 7–10 days | Classical Protocol | 1–3 days | Sulphadiazine, tetracyclines, ciprofloxacin, streptomycin, novo biocin, gentamicin, imipenem, ceftazidime |
| Q Fever | B | 10–40 days | 2–14 days | Classical Protocol | 7–14 days | Tetracycline, doxycycline |
| Viral encephalitides | B | 2–6 days | 2–21 days | Level D Protocol | 1–3 days | Supportive care |
| Ricin toxin | B | 18–24 hr | 1–12 days | Level D Protocol | 1–5 days | Supportive care |

*Adapted from REF 137. [‡]From the Emergency Preparedness and Response website of the Centers for Disease Control and Prevention (<http://www.bt.cdc.gov>). Surveillance laboratories (level A); national laboratories (level D)

the highest dose of anthrax spores during the 2001 anthrax attacks, the mean duration between exposure and onset of disease was 4.5 days. Disease onset in these cases would be prior to the development of a robust humoral antibody response. Moreover, the need to collect paired acute and convalescent sera could limit the usefulness of these assays as epidemiological tools.

Bioagent-directed detection. Promising new technologies could enable the early recognition of replicating aetiological agents and their virulence factors. Potentially, the amplification of variable gene regions flanked by conserved sequences, followed by electrospray ionization mass spectrometry and base-composition

analysis of the products could be one approach. This approach, called triangulation identification for genetic evaluation of risks (TIGER)¹⁴⁷, provides a high-throughput, multiple detection and identification system for nearly all known, newly emergent and bioengineered agents in a single test. This rapid, robust and culture-free system has been used to identify agents such as severe acute respiratory syndrome (SARS)-related coronavirus before their recognition by traditional methods. Robust and portable systems have been proposed for the development of civilian and military applications.

Biosensing represents another evolving mechanism for early detection. Here, single proteinaceous nanometer-scale pores (such as anthrax PA) can be easily applied to provide the physical basis for rapid biosensing applications. The mechanism of nanopore-based detection is simple: analytes that either bind to the nanopore or thread through it alter the ionic current in a characteristic manner. For example, the reversible binding of hydronium and deuterium ions to the α -hemolysin ion channel causes current fluctuations with amplitude and spectral signatures that indicate the type and concentration of the isotope that is present¹⁴⁸. The same ion channel was also used to detect and characterize individual molecules of single-stranded DNA that are driven electrophoretically through the pore¹⁴⁹. This latter technology was used to detect other analytes in solution.

Box 2 | The necessity for BSAT rapid detection

During the 2001 anthrax attacks, although several patients had exposure to anthrax spores confirmed by nasal swab culture, no cases of disease occurred in the ~32,000 Senate staff and postal workers immediately targeted for post-exposure chemoprophylaxis^{140,170}. By contrast, the post-syndromic group of inhalation anthrax-infected patients had a case mortality rate of approximately 45%¹⁴¹. These data were consistent with other studies that suggested that early and aggressive treatment is necessary to influence survival after exposure to inhalation anthrax^{171,172}.

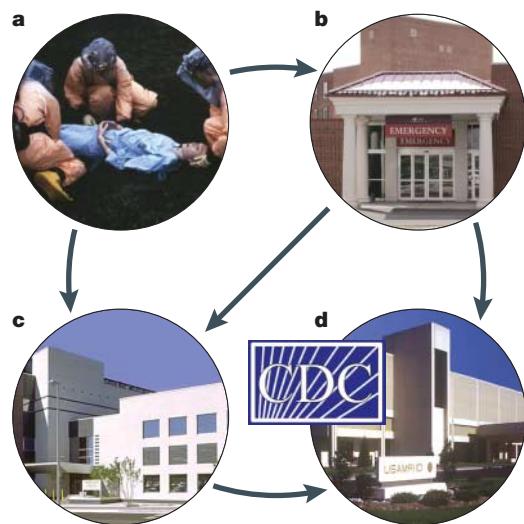


Figure 3 | A schematic of how components of the national laboratory response network (LRN) coordinate when detecting and diagnosing a biothreat agent. **a** | Initial responders collect evidence, which is then sent to surveillance laboratories or to confirmatory laboratories directly (**b,c**). Cooperation between these laboratories facilitates first line response procedures. **d** | Further confirmation of agent type and area of distribution, is then conducted at national laboratories.

Specifically, analytes of interest that bind to sites on pore-permeant polynucleotides alter the ability of the DNA to enter and thread through the pore¹⁵⁰. These approaches can be extended into biosensing of anthrax toxin at pM amounts (J. Kasianowicz and K. Halverson, personal communication).

Box 3 | BioWatch and Biosense limitations

Although the BioWatch and BioSense Programs represent significant improvements in biological defence readiness, they could, however, fail to influence morbidity and mortality in the case of an attack. BioWatch will probably document an attack when a biological threat agent is used on the scale of a weapon of mass destruction. However, extensive epidemiological surveillance might still be necessary before wide-scale prophylaxis is implemented. Another issue that is yet to be resolved is whether environmental sampling is sufficient to trigger a wide-scale medical response. The FDA might have to review environmental detection technologies if they influence medical decision-making. A measured and conservative approach is likely. During the 2001 anthrax attacks, Senate workers were screened and successfully treated after initial environmental test results were confirmed. But treatment of other populations might have been delayed by confusion and the lack of reliable laboratory confirmation¹⁴⁵. BioWatch samplers might not be effective for limited attacks on individuals or contamination of water and food sources. In the case of BioSense, surrogate markers of infectious disease outbreaks can only be lagging indicators of an attack. There could be hundreds or thousands of cases before an outbreak is recognized, depending on the sensitivity of the final system. Smallpox virus has a comparatively long incubation time of up to 17 days (TABLE 10). By the time BioSense detects a smallpox attack, multiple foci of infection across the country, with coincident close contact spread, would most likely already be developing using current disease models^{173,174}.

Host-directed detection. A powerful approach for identifying exposed or infected individuals is to develop highly specific and extremely sensitive innate biomarkers that can be detected very early after exposure to a biological agent. There are a number of different types of biomarkers, but one of the most effective methods for identifying highly specific and acutely sensitive biomarkers is through the use of gene- and protein-expression-profiling technologies^{151–153}. The advantage of gene-expression studies is that they are large-scale (able to monitor gene-expression changes across an entire genome in one assay), high throughput and highly cost effective (relative to other methods). For example, one of the areas in which this technology has received the greatest attention is in identifying biomarkers for cancer, a field in which expression profiling has been accepted as a powerful tool for identifying specific biomarkers for disease progression, and discriminating between different subtypes of cancer, and, in some cases, identifying biomarkers for susceptibility to specific therapeutics^{154–156}.

With regard to infectious diseases, expression profiling of human neutrophils exposed to bacteria reveals dramatic changes in the level of hundreds of mRNA species, including those for cytokines, receptors, membrane-trafficking regulators and genes involved in apoptosis¹⁵⁵. More importantly, expression profiling of the neutrophil response indicates that key differences in mRNA-expression patterns could be detected on the basis of whether the cells were exposed to pathogenic or non-pathogenic bacteria. Other studies of virus–host interactions using expression technologies and genomic systems studies of host–pathogen interactions have identified specific host factors that pathogens can subvert to optimize their replication and life cycle^{154,156}.

Recently, gene-expression-profiling technologies have been applied to the identification of biomarkers for predicting the toxicity of compounds. The field of toxicogenomics has received much interest in both the commercial and academic sectors because of its capability to successfully predict the toxicity of compounds in drug development research, as well as in environmental studies¹⁵⁷. Existing expertise could be harnessed and applied to developing predictive models to assess the extent of exposure to a biological agent, disease progression and to predict clinical outcomes.

In the future, the creation of a widely available human-gene-expression database of responses to biological threat agents would be extremely beneficial for the rapid and decisive identification of each agent — via a quick and simple blood test. Traditional methods for the identification of biological agents have focused on identifying the agent itself rather than identifying host response. However, many biological agents, such as haemorrhagic fever viruses, could be infectious at levels well below the limit of detection afforded by current technologies. Because the human innate immune system is an exquisitely refined, highly sensitive and highly specific detection system for pathogens, monitoring changes in host innate response via biomarkers is a novel method for identifying exposure to biowarfare agents at very early time points.

Challenges and future trends

The work reviewed in this manuscript provides evidence that the scientific community has not turned a blind eye to countering bioterrorist agents, but has responded with a massive effort that has resulted in a steep and productive learning curve. This effort has been facilitated by timely and significant increases in support from funding agencies. However, there is a serious lack of organization in how biodefence is currently addressed. Our existing preparedness and response measures are not sufficient to meet the challenges of a bioterrorist attack¹⁵⁸. This is due not only to a lack of cooperation and coordination, but also to ineffective detection networks, a lack of time-effective diagnostic methodologies and the dearth of a clear vision and strategy to translate all of the publicly funded biodefence research into useful therapies and antidotes. These issues can be easily mitigated with a unified plan of action, orchestrated by a central entity overseeing a comprehensive and organized approach to biodefence. We foresee such a central entity playing a pivotal role in ensuring that cross-communication between agencies is

facilitated, and that research is focused and completed in a timely manner. In addition, as potential new therapeutics emerge from the drug discovery pipeline, greater involvement from the pharmaceutical industry will be required. It is an accepted fact that the industry is adept at translational research — that is, rapidly and effectively converting potential therapies into approved drugs. However, incentives will need to be put in place to encourage the pharmaceutical industry to conduct such costly studies, and this is where a unifying biodefence entity can have a major facilitating role. Presently, project Bioshield is a start, but needs serious improvements. The ability to develop new therapeutics, and their approval as drugs that can be strategically stockpiled, is urgent. However, new technologies for detecting the release of bioterrorist agents, and timely protocols for the specific diagnosis of a bioterrorist agent that has been used, will be needed; this in turn could prevent the chaos that was experienced during the anthrax attacks of 2001. If we start making plans today, and unify our efforts, it will be possible to create a true biodefence shield that will effectively curtail future acts of bioterror.

1. Duesbery, N. S. *et al.* Proteolytic inactivation of MAP-kinase-kinase by anthrax lethal factor. *Science* **280**, 734–737 (1998).
2. Vitale, G. *et al.* Anthrax lethal factor cleaves the N-terminus of MAPKs and induces tyrosine/threonine phosphorylation of MAPKs in cultured macrophages. *Biochem. Biophys. Res. Commun.* **248**, 706–711 (1998).
3. Drum, C. L. *et al.* Structural basis for the activation of anthrax adenyl cyclase exotoxin by calmodulin. *Nature* **415**, 396–402 (2002).
4. Scobie, H. M., Rainey, G. J., Bradley, K. A. & Young, J. A. Human capillary morphogenesis protein 2 functions as an anthrax toxin receptor. *Proc. Natl. Acad. Sci. USA* **100**, 5170–5174 (2003).
5. Bradley, K. A., Mogridge, J., Mourez, M., Collier, R. J. & Young, J. A. Identification of the cellular receptor for anthrax toxin. *Nature* **414**, 225–229 (2001).
6. Santelli, E., Bankston, L. A., Leppa, S. H. & Liddington, R. C. Crystal structure of a complex between anthrax toxin and its host cell receptor. *Nature* **430**, 905–908 (2004).
7. Klimpel, K. R., Molloy, S. S., Thomas, G. & Leppa, S. H. Anthrax toxin protective antigen is activated by a cell surface protease with the sequence specificity and catalytic properties of furin. *Proc. Natl. Acad. Sci. USA* **89**, 10277–10281 (1992).
8. Cameron, A., Appel, J., Houghten, R. A. & Lindberg, I. Polyarginines are potent furin inhibitors. *J. Biol. Chem.* **275**, 36741–36749 (2000).
9. Sarac, M. S., Peinado, J. R., Leppa, S. H. & Lindberg, I. Protection against anthrax toxemia by hexa-d-arginine *in vitro* and *in vivo*. *Infect. Immun.* **72**, 602–605 (2004).
10. Kacprzak, M. M. *et al.* Inhibition of furin by polyarginine-containing peptides: nanomolar inhibition by nona-d-arginine. *J. Biol. Chem.* **279**, 36788–36794 (2004).
11. Sellman, B. R., Mourez, M. & Collier, R. J. Dominant-negative mutants of a toxin subunit: an approach to therapy of anthrax. *Science* **292**, 695–697 (2001).
12. Singh, Y., Khanna, H., Chopra, A. P. & Mehra, V. A dominant negative mutant of *Bacillus anthracis* protective antigen inhibits anthrax toxin action *in vivo*. *J. Biol. Chem.* **276**, 22090–22094 (2001).
13. Mourez, M. *et al.* Designing a polyvalent inhibitor of anthrax toxin. *Nature Biotechnol.* **19**, 958–961 (2001).
14. Nguyen, T. L. Three-dimensional model of the pore form of anthrax protective antigen. Structure and biological implications. *J. Biomol. Struct. Dyn.* **22**, 253–265 (2004).
15. Hammond, S. E. & Hanna, P. C. Lethal factor active-site mutations affect catalytic activity *in vitro*. *Infect. Immun.* **66**, 2374–2378 (1998).
16. Tonello, F., Seveso, M., Marin, O., Mock, M. & Montecucco, C. Screening inhibitors of anthrax lethal factor. *Nature* **418**, 386 (2002).
17. Turk, B. E. *et al.* The structural basis for substrate and inhibitor selectivity of the anthrax lethal factor. *Nature Struct. Mol. Biol.* **11**, 60–66 (2004).
18. Cummings, R. T. *et al.* A peptide-based fluorescence resonance energy transfer assay for *Bacillus anthracis* lethal factor protease. *Proc. Natl. Acad. Sci. USA* **99**, 6603–6606 (2002).
19. Panchal, R. G. *et al.* Identification of small molecule inhibitors of anthrax lethal factor. *Nature Struct. Mol. Biol.* **11**, 67–72 (2004).
20. Min, D. H., Tang, W. J. & Mrksich, M. Chemical screening by mass spectrometry to identify inhibitors of anthrax lethal factor. *Nature Biotechnol.* **22**, 717–723 (2004).
21. Dell'Aica, I. *et al.* Potent inhibitors of anthrax lethal factor from green tea. *EMBO Rep.* **5**, 418–422 (2004).
22. Lee, L. V. *et al.* Inhibition of the proteolytic activity of anthrax lethal factor by aminoglycosides. *J. Am. Chem. Soc.* **126**, 4774–4775 (2004).
23. Soelaiman, S. *et al.* Structure-based inhibitor discovery against adenyl cyclase toxins from pathogenic bacteria that cause anthrax and whooping cough. *J. Biol. Chem.* **278**, 25990–25997 (2003).
24. Shen, Y. *et al.* Selective inhibition of anthrax edema factor by adefovir, a drug for chronic hepatitis B virus infection. *Proc. Natl. Acad. Sci. USA* **101**, 3242–3247 (2004).
25. Paddle, B. M. Therapy and prophylaxis of inhaled biological toxins. *J. Appl. Toxicol.* **23**, 139–170 (2003).
26. Rainey, G. J. & Young, J. A. Antitoxins: novel strategies to target agents of bioterrorism. *Nature Rev. Microbiol.* **2**, 721–726 (2004).
27. Dong, M. *et al.* Synaptotagmins I and II mediate entry of botulinum neurotoxin B into cells. *J. Cell. Biol.* **162**, 1293–1303 (2003).
28. Yowler, B. C., Kensinger, R. D. & Schengrund, C. L. Botulinum neurotoxin A activity is dependent upon the presence of specific gangliosides in neuroblastoma cells expressing synaptotagmin I. *J. Biol. Chem.* **277**, 32815–32819 (2002).
29. Armon, S. S. *et al.* Botulinum toxin as a biological weapon: medical and public health management. *JAMA* **285**, 1059–1070 (2001).
30. Singh, B. R. Intimate details of the most poisonous poison. *Nature Struct. Biol.* **7**, 617–619 (2000).
31. Turton, K., Chaddock, J. A. & Acharya, K. R. Botulinum and tetanus neurotoxins: structure, function and therapeutic utility. *Trends Biochem. Sci.* **27**, 552–558 (2002).
32. Deshpande, S. S., Sheridan, R. E. & Adler, M. Efficacy of certain quinolines as pharmacological antagonists in botulinum neurotoxin poisoning. *Toxicol.* **35**, 433–445 (1997).
33. Sheridan, R. E., Deshpande, S. S., Nicholson, J. D. & Adler, M. Structural features of aminoquinolines necessary for antagonist activity against botulinum neurotoxin. *Toxicol.* **35**, 1439–1451 (1997).
34. Eswaramoorthy, S., Kumaran, D. & Swaminathan, S. Crystallographic evidence for doxorubicin binding to the receptor-binding site in *Clostridium botulinum* neurotoxin B. *Acta Crystallogr. D Biol. Crystallogr.* **57**, 1743–1746 (2001).
35. Hayden, J., Pires, J., Roy, S., Hamilton, M. & Moore, G. J. Discovery and design of novel inhibitors of botulinum neurotoxin A: targeted 'hinge' peptide libraries. *J. Appl. Toxicol.* **23**, 1–7 (2003).
36. Schmidt, J. J. & Stafford, R. G. A high-affinity competitive inhibitor of type A botulinum neurotoxin protease activity. *FEBS Lett.* **532**, 423–426 (2002).
37. Schmidt, J. J. & Bostian, K. A. Proteolysis of synthetic peptides by type A botulinum neurotoxin. *J. Protein Chem.* **14**, 703–708 (1995).
38. Schmidt, J. J. & Bostian, K. A. Endoproteinase activity of type A botulinum neurotoxin: substrate requirements and activation by serum albumin. *J. Protein Chem.* **16**, 19–26 (1997).
39. Schmidt, J. J., Stafford, R. G. & Bostian, K. A. Type A botulinum neurotoxin proteolytic activity: development of competitive inhibitors and implications for substrate specificity at the S1' binding subsite. *FEBS Lett.* **435**, 61–64 (1998).
40. Sukonpan, C. *et al.* Synthesis of substrates and inhibitors of botulinum neurotoxin type A metalloprotease. *J. Pept. Res.* **63**, 181–193 (2004).
41. Burnett, J. C. *et al.* Novel small molecule inhibitors of botulinum neurotoxin A metalloprotease activity. *Biochem. Biophys. Res. Commun.* **310**, 84–93 (2003).

The first small molecule (non-peptidic) inhibitors of botulinum neurotoxin serotype A are described, and a pharmacophore for inhibition is proposed.

42. Segelke, B., Knapp, M., Kadkhodayan, S., Balhorn, R. & Rupp, B. Crystal structure of Clostridium botulinum neurotoxin protease in a product-bound state: Evidence for noncanonical zinc protease activity. *Proc. Natl. Acad. Sci. USA* **101**, 6888–6893 (2004).

43. Lacy D. B., Tepp, W., Cohen, A. C., DasGupta, B. R. & Stevens, R. C. Crystal structure of botulinum neurotoxin type A and implications for toxicity. *Nature Struct. Biol.* **5**, 898–902 (1998).

44. Breidenbach, M. A. & Brunger, A. T. Substrate recognition strategy for botulinum neurotoxin serotype A. *Nature* **432**, 925–929 (2004).

45. Zhou, J. Y., Wang, Z. F., Ren, X. M., Tang, M. Z. & Shi, Y. L. Antagonism of botulinum toxin type A-induced cleavage of SNAP-25 in rat cerebral synaptosome by toosendanin. *FEBS Lett.* **555**, 375–379 (2003).

46. Adler, M., Nicholson, J. D., Cornille, F. & Hackley, B. E., Jr. Efficacy of a novel metalloprotease inhibitor on botulinum neurotoxin B activity. *FEBS Lett.* **429**, 234–238 (1998).

47. Eswaramoorthy, S., Kumaran, D. & Swaminathan, S. A novel mechanism for Clostridium botulinum neurotoxin inhibition. *Biochemistry* **41**, 9795–9802 (2002).

48. Adler, M. *et al.* Evaluation of phosphoramidon and three synthetic phosphonates for inhibition of botulinum neurotoxin B catalytic activity. *J. Appl. Toxicol.* **19** (Suppl. 1), S5–S11 (1999).

49. Garcia, G. E., Moorad, D. R. & Gordon, R. K. Buforin I, a natural peptide, inhibits botulinum neurotoxin B activity *in vitro*. *J. Appl. Toxicol.* **19** (Suppl. 1), S19–S22 (1999).

50. Schmidt, J. J. & Stafford, R. G. Fluorogenic substrates for the protease activities of botulinum neurotoxins, serotypes A, B, and F. *Appl. Environ. Microbiol.* **69**, 297–303 (2003).

51. Roques, B. P., Anne, C., Turcaud, S. & Fournie-Zaluski, M. C. Mechanism of action of clostridial neurotoxins and rational inhibitor design. *Biol. Cell.* **92**, 445–447 (2000).

52. Anne, C. *et al.* Development of potent inhibitors of botulinum neurotoxin type B. *J. Med. Chem.* **46**, 4648–4656 (2003).

53. Anne, C. *et al.* Thio-derived disulfides as potent inhibitors of botulinum neurotoxin type B: Implications for zinc interaction. *Bioorg. Med. Chem.* **11**, 4655–4660 (2003).

54. Blommaert, A., Turcaud, S., Anne, C. & Roques, B. P. Small tripeptide surrogates with low nanomolar affinity as potent inhibitors of the botulinum neurotoxin B metallo-proteolytic activity. *Bioorg. Med. Chem.* **12**, 3055–3062 (2004).

55. Monzingo, A. F. & Robertus, J. D. X-ray analysis of substrate analogs in the ricin A-chain active site. *J. Mol. Biol.* **227**, 1136–1145 (1992).

56. Yan, X. *et al.* Structure-based identification of a ricin inhibitor. *J. Mol. Biol.* **266**, 1043–1049 (1997).

57. Miller, D. J., Ravikumar, K., Shen, H., Suh, J. K., Kerwin, S. M., Robertus, J. D. Structure-based design and characterization of novel platform for ricin and shiga toxin inhibition. *J. Med. Chem.* **45**, 90–98 (2002).

58. Nimjee, S. M., Rusconi, C. P. & Sullenger, B. A. APTAMERS: an emerging class of therapeutics. *Annu. Rev. Med.* **56**, 555–583 (2005).

The review gives and account of the evolution of aptamers as therapeutics and speculates on the clinical usefulness of these compounds.

59. Hesselberth, J. R., Miller, D., Robertus, J. & Ellington, A. D. In vitro selection of RNA molecules that inhibit the activity of ricin A-chain. *J. Biol. Chem.* **275**, 4937–4942 (2000).

60. Tanaka, K. S. *et al.* Ricin A-chain inhibitors resembling the oxacarbenium ion transition state. *Biochemistry* **40**, 6845–6851 (2001).

61. Chen, X. Y., Link, T. M. & Schramm, V. L. Ricin A-chain: kinetics, mechanism, and RNA stem-loop inhibitors. *Biochemistry* **37**, 11605–11613 (1998).

62. Schlievert, P. M. Use of intravenous immunoglobulin in the treatment of staphylococcal and streptococcal toxic shock syndromes and related illnesses. *J. Allergy Clin. Immunol.* **108**, S107–S110 (2001).

63. LeClaire, R. D., Kell, W., Bavari, S., Smith, T. J. & Hunt, R. E. Protective effects of niacinamide in staphylococcal enterotoxin B-induced toxicity. *Toxicology* **107**, 69–81 (1996).

64. Tarkowski, A. *et al.* Microbial superantigens as virulence factors and ways to counteract their actions. *Scand. J. Infect. Dis.* **35**, 642–646 (2003).

65. Kieke, M. C. *et al.* High affinity T cell receptors from yeast display libraries block T cell activation by superantigens. *J. Mol. Biol.* **307**, 1305–1315 (2001).

66. Hong-Geller, E. & Gupta, G. Therapeutic approaches to superantigen-based diseases: a review. *J. Mol. Recognit.* **16**, 91–101 (2003).

67. Shalubhai, K. Bioterrorism: a new frontier for drug discovery and development. *Drugs* **6**, 773–780 (2003).

68. Kaempfer, R. Peptide antagonists of superantigen toxins. *Mol. Divers.* **8**, 113–120 (2004).

69. Rajagopalan, G., Sen, M. M. & David, C. S. *In vitro* and *in vivo* evaluation of staphylococcal superantigen peptide antagonists. *Infect. Immun.* **72**, 6733–6737 (2004).

70. Arad, G., Levy, R., Hillman, D. & Kaempfer, R. Superantigen antagonist protects against lethal shock and defines a new domain for T-cell activation. *Nature Med.* **6**, 414–421 (2000).

71. De Clercq, E. Antiviral drugs in current clinical use. *J. Clin. Virol.* **30**, 115–133 (2004).

Review that covers antiviral drugs in clinical use.

72. Chan, S. Y. *et al.* Folate receptor- α is a cofactor for cellular entry by Marburg and Ebola viruses. *Cell* **106**, 117–126 (2001).

73. Becker, S., Spiess, M. & Klenk, H. D. The asialoglycoprotein receptor is a potential liver-specific receptor for Marburg virus. *J. Gen. Virol.* **76** (Pt 2), 393–399 (1995).

74. Takada, A. *et al.* Human macrophage C-type lectin specific for galactose and N-acetylgalactosamine promotes filovirus entry. *J. Virol.* **78**, 2943–2947 (2004).

75. Simmons, G. *et al.* DC-SIGN and DC-SIGNR bind ebola glycoproteins and enhance infection of macrophages and endothelial cells. *Virology* **305**, 115–123 (2003).

76. Barrientos, L. G. & Gronerborn, A. M. The highly specific carbohydrate-binding protein cyanovirin-n: structure, anti-HIV/ebola activity and possibilities for therapy. *Mini. Rev. Med. Chem.* **5**, 21–31 (2005).

77. Harrison, S. C. *et al.* Discovery of antivirals against smallpox. *Proc. Natl. Acad. Sci. USA* **101**, 11178–11192 (2004).

78. Watanabe, S. *et al.* Functional importance of the coiled-coil of the Ebola virus glycoprotein. *J. Virol.* **74**, 10194–10201 (2000).

79. Weissenhorn, W., Calder, L. J., Wharton, S. A., Skehel, J. J. & Wiley, D. C. The central structural feature of the membrane fusion protein subunit from the Ebola virus glycoprotein is a long triple-stranded coiled coil. *Proc. Natl. Acad. Sci. USA* **95**, 6032–6036 (1998).

80. Weissenhorn, W., Carfi, A., Lee, K. H., Skehel, J. J. & Wiley, D. C. Crystal structure of the Ebola virus membrane fusion subunit, GP2, from the envelope glycoprotein ectodomain. *Mol. Cell* **2**, 605–616 (1998).

81. Aman, M. J. *et al.* Molecular mechanisms of filovirus cellular trafficking. *Microbes Infect.* **5**, 639–649 (2003).

82. Goodchild, J. Oligonucleotide, antibody and peptide therapeutics – from design to the clinic. *Curr. Opin. Mol. Ther.* **6**, 119 (2004).

83. Muhilberger, E., Weik, M., Volchkov, V. E., Klenk, H. D. & Becker, S. Comparison of the transcription and replication strategies of marburg virus and Ebola virus by using artificial replication systems. *J. Virol.* **73**, 2333–2342 (1999).

84. Towner, J. S. *et al.* Generation of eGFP expressing recombinant Zaire ebolavirus for analysis of early pathogenesis events and high-throughput antiviral drug screening. *Virology* **332**, 20–27 (2005).

85. Siegert, R., Shu, H. L. & Slenczka, W. Isolation and identification of the 'Marburg virus'. *Ger. Med. Mon.* **13**, 514–518 (1968).

86. Geisbert, T. W. & Jahrling, P. B. Differentiation of filoviruses by electron microscopy. *Virus Res.* **39**, 129–150 (1995).

87. Bavari, S. *et al.* Lipid raft microdomains: a gateway for compartmentalized trafficking of Ebola and Marburg viruses. *J. Exp. Med.* **195**, 593–602 (2002).

88. Neumann, G., Feldmann, H., Watanabe, S., Lukashevich, I. & Kawaoka, Y. Reverse genetics demonstrates that proteolytic processing of the Ebola virus glycoprotein is not essential for replication in cell culture. *J. Virol.* **76**, 406–410 (2002).

89. Cono, J., Casey, C. G. & Bell, D. M. Smallpox vaccination and adverse reactions. Guidance for clinicians. *MMWR Recomm. Rep.* **52**, 1–28 (2003).

90. Geisbert, T. W. *et al.* Mechanisms underlying coagulation abnormalities in ebola hemorrhagic fever: overexpression of tissue factor in primate monocytes/macrophages is a key event. *J. Infect. Dis.* **188**, 1618–1629 (2003).

91. Geisbert, T. W. *et al.* Treatment of Ebola virus infection with a recombinant inhibitor of factor VIIa/tissue factor: a study in rhesus monkeys. *Lancet* **362**, 1953–1958 (2003).

This is one of the first examples of host-directed therapeutics for filoviruses. The report suggests the therapeutic targeting of the sequential lifecycles of pathogenic filoviruses, such as the coagulation processes, may have beneficial outcomes.

92. Schmaljohn, A. L., Johnson, E. D., Dalrymple, J. M. & Cole, G. A. Non-neutralizing monoclonal antibodies can prevent lethal alphavirus encephalitis. *Nature* **297**, 70–72 (1982).

93. Hart, M. K. Vaccine research efforts for filoviruses. *Int. J. Parasitol.* **33**, 583–595 (2003).

94. Hevey, M., Negley, D., Geisbert, J., Jahrling, P. & Schmaljohn, A. Antigenicity and vaccine potential of Marburg virus glycoprotein expressed by baculovirus recombinants. *Virology* **239**, 206–216 (1997).

95. Hevey, M., Negley, D. & Schmaljohn, A. Characterization of monoclonal antibodies to Marburg virus (strain Musoke) glycoprotein and identification of two protective epitopes. *Virology* **314**, 350–357 (2003).

96. Wilson, J. A. *et al.* Epitopes involved in antibody-mediated protection from Ebola virus. *Science* **287**, 1664–1666 (2000).

The first report of a monoclonal antibody treatment for ebola virus that showed *in vivo* protection.

97. Jahrling, P. B. *et al.* Passive immunization of Ebola virus-infected cynomolgus monkeys with immunoglobulin from hyperimmune horses. *Arch. Virol. Suppl.* **11**, 135–140 (1996).

98. Hevey, M., Negley, D., Pushko, P., Smith, J. & Schmaljohn, A. Marburg virus vaccines based upon alphavirus replicons protect guinea pigs and nonhuman primates. *Virology* **251**, 28–37 (1998).

The first demonstration of an efficacious vaccine against filoviruses.

99. Ignatov, G. M. Immune response to filovirus infections. *Curr. Top. Microbiol. Immunol.* **235**, 205–217 (1999).

100. Vanderzanden, L. *et al.* DNA vaccines expressing either the GP or NP genes of Ebola virus protect mice from lethal challenge. *Virology* **246**, 134–144 (1998).

101. Wilson, J. A. & Hart, M. K. Protection from Ebola virus mediated by cytotoxic T lymphocytes specific for the viral nucleoprotein. *J. Virol.* **75**, 2660–2664 (2001).

102. Xu, L. *et al.* Immunization for Ebola virus infection. *Nature Med.* **4**, 37–42 (1998).

103. Martini, G. A. R. S. *Marburg Virus Disease* (Springer-Verlag, Berlin New York, 1971).

104. Mupapa, K. *et al.* Treatment of Ebola hemorrhagic fever with blood transfusions from convalescent patients. International Scientific and Technical Committee. *J. Infect. Dis.* **179** (Suppl. 1), S18–S23 (1999).

105. Boulter, E. A. & Appleyard, G. Differences between extracellular and intracellular forms of poxvirus and their implications. *Prog. Med. Virol.* **16**, 86–108 (1973).

106. Hooper, J. W., Custer, D. M., Schmaljohn, C. S. & Schmaljohn, A. L. DNA vaccination with vaccinia virus L1R and A33R genes protect mice against a lethal poxvirus challenge. *Virology* **266**, 329–339 (2000).

107. Hooper, J. W. *et al.* Smallpox DNA vaccine protects nonhuman primates against lethal monkeypox. *J. Virol.* **78**, 4433–4443 (2004).

108. Galimberti, M. C., Goenaga, J., Wittek, R. & Rindisbacher, L. Neutralizing and protective antibodies directed against vaccinia virus envelope antigens. *Virology* **254**, 71–80 (1999).

109. Schmaljohn, A. L., Kokubun, K. M. & Cole, G. A. Protective monoclonal antibodies define maturational and pH-dependent antigenic changes in Sindbis virus E1 glycoprotein. *Virology* **130**, 144–154 (1983).

110. Bell, E. *et al.* Antibodies against the extracellular enveloped virus B5R protein are mainly responsible for the EEE neutralizing capacity of vaccinia immune globulin. *Virology* **325**, 425–431 (2004).

111. Mohamadzadeh, M. & Luftig, R. Dendritic cells: in the forefront of immunopathogenesis and vaccine development — a review. *J. Immune Based Ther. Vaccines* **2**, 1 (2004).

112. Palese, P., Muster, T., Zheng, H., O'Neill, R. & Garcia-Sastre, A. Learning from our foes: a novel vaccine concept for influenza virus. *Arch. Virol. Suppl.* **15**, 131–138 (1999).

113. Chang, H. W., Watson, J. C. & Jacobs, B. L. The E3L gene of vaccinia virus encodes an inhibitor of the interferon-induced, double-stranded RNA-dependent protein kinase. *Proc. Natl. Acad. Sci. USA* **89**, 4825–4829 (1992).

114. Basler, C. F. *et al.* The Ebola virus VP35 protein functions as a type I IFN antagonist. *Proc. Natl. Acad. Sci. USA* **97**, 12289–12294 (2000).

115. Bosio, C. M. *et al.* Ebola and Marburg viruses replicate in monocyte-derived dendritic cells without inducing the production of cytokines and full maturation. *J. Infect. Dis.* **188**, 1630–1638 (2003).

116. Seet, B. T. *et al.* Poxviruses and immune evasion. *Annu. Rev. Immunol.* **21**, 377–423 (2003).

117. Warfield, K. L. *et al.* Ebola virus-like particles protect from lethal Ebola virus infection. *Proc. Natl. Acad. Sci. USA* **100**, 15889–15894 (2003).

118. Pornillos, O., Garrus, J. E. & Sundquist, W. I. Mechanisms of enveloped RNA virus budding. *Trends Cell Biol.* **12**, 569–579 (2002).

REVIEWS

119. Moss, B. & Ward, B. M. High-speed mass transit for poxviruses on microtubules. *Nature Cell Biol.* **3**, E245–E246 (2001).

120. Bieniasz, P. Intrinsic immunity: a front-line defense against viral attack. *Nature Immunol.* **5**, 1109–1115 (2004).

121. Grandvaux, N., tenOever, B. R., Servant, M. J. & Hiscott, J. The interferon antiviral response: from viral invasion to evasion. *Curr. Opin. Infect. Dis.* **15**, 259–267 (2002).

122. Heine H., D. R. a. A. G. in 41st Interscience Conference on Antimicrobial Agents and Chemotherapy (Chicago, IL, 2001).

123. Heine H., D. R. a. B. W. in 40th Interscience Conference on Antimicrobial Agents and Chemotherapy (Toronto, Canada, 2000).

124. Inglesby, T. V. *et al.* Anthrax as a biological weapon, 2002: updated recommendations for management. *JAMA* **287**, 2236–2252 (2002).

125. Bartlett, J. G., Inglesby, T. V., Jr. & Borio, L. Management of anthrax. *Clin. Infect. Dis.* **35**, 851–858 (2002).

126. Pomerantsev, A. P., Shishkova, N. A. & Marinin, L. I. [Comparison of therapeutic effects of antibiotics of the tetracycline group in the treatment of anthrax caused by a strain inheriting tet-gene of plasmid pBC16]. *Antibiot. Khimioter.* **37**, 31–34 (1992).

127. Stepanov, A. V., Marinin, L. I., Pomerantsev, A. P. & Staritsin, N. A. Development of novel vaccines against anthrax in man. *J. Biotechnol.* **44**, 155–160 (1996).

128. Vasil'ev, N. T. *et al.* [Sensitivity spectrum of Francisella tularensis to antibiotics and synthetic antibacterial drugs]. *Antibiot. Khimioter.* **34**, 662–665 (1989).

129. Scheel, O., Hoel, T., Sandvik, T. & Berdal, B. P. Susceptibility pattern of Scandinavian Francisella tularensis isolates with regard to oral and parenteral antimicrobial agents. *APMIS* **101**, 33–36 (1993).

130. Maurin, M., Mersali, N. F. & Raoult, D. Bactericidal activities of antibiotics against intracellular Francisella tularensis. *Antimicrob. Agents Chemother.* **44**, 3428–3431 (2000).

131. Kudelina, R. I. & Olsufiev, N. G. Sensitivity to macrolide antibiotics and lincomycin in Francisella tularensis holarktika. *J. Hyg. Epidemiol. Microbiol. Immunol.* **24**, 84–91 (1980).

132. Ikaheimo, I., Syrjala, H., Karhukorpi, J., Schildt, R. & Koskela, M. *In vitro* antibiotic susceptibility of Francisella tularensis isolated from humans and animals. *J. Antimicrob. Chemother.* **46**, 287–290 (2000).

133. Baker, C. N., Hollis, D. G. & Thornsberry, C. Antimicrobial susceptibility testing of Francisella tularensis with a modified Mueller–Hinton broth. *J. Clin. Microbiol.* **22**, 212–215 (1985).

134. Dennis, D. T. *et al.* Tularemia as a biological weapon: medical and public health management. *JAMA* **285**, 2763–73 (2001).

135. Ellis, J., Oyston, P. C., Green, M. & Titball, R. W. Tularemia. *Clin. Microbiol. Rev.* **15**, 631–646 (2002).

136. Perez-Castrillon, J. L., Bachiller-Luque, P., Martin-Luquero, M., Mena-Martin, F. J. & Herreros, V. Tularemia epidemic in northwestern Spain: clinical description and therapeutic response. *Clin. Infect. Dis.* **33**, 573–576 (2001).

137. Henchal, E. A., Teska, J. D., Ludwig, G. V., Shoemaker, D. R. & Ezzell, J. W. Current laboratory methods for biological threat agent identification. *Clin. Lab. Med.* **21**, 661–678 (2001).

138. Gilchrist, M. J. A national laboratory network for bioterrorism: evolution from a prototype network of laboratories performing routine surveillance. *Mil. Med.* **165**, 28–31 (2000).

139. Gilchrist, M. J. R., W. P. McKinney, J. M. Miller, and A. S. Weissfeld. Laboratory safety, management and diagnosis of biological agents associated with bioterrorism (ed. Snyder, J. W.) (ASM Press, Washington, DC, 2000).

140. Jernigan, D. B. *et al.* Investigation of bioterrorism-related anthrax, United States, 2001: epidemiologic findings. *Emerg. Infect. Dis.* **8**, 1019–1028 (2002).

141. Jernigan, J. A. *et al.* Bioterrorism-related inhalational anthrax: the first 10 cases reported in the United States. *Emerg. Infect. Dis.* **7**, 933–944 (2001).

142. (Health Alert Network, 2003).

143. Marburg, J. In *Biosecurity 2003* (Washington, DC, 2003).

144. (National Association of Letter Carriers, 2003).

145. In U. S. Senate Committee on Environment and Public Works (Environmental Protection Agency, 2001).

146. Sirisanthana, T., Nelson, K. E., Ezzell, J. W. & Abshire, T. G. Serological studies of patients with cutaneous and oral-pharyngeal anthrax from northern Thailand. *Am. J. Trop. Med. Hyg.* **39**, 575–581 (1988).

147. Hofstadler, S. A. *et al.* TIGER: the universal biosensor. *Int. J. Mass Spectrometry* **12844**, 1–18 (2004).

148. Kasianowicz, J. J. & Bezrukov, S. M. Protonation dynamics of the alpha-toxin ion channel from spectral analysis of pH-dependent current fluctuations. *Biophys. J.* **69**, 94–105 (1995).

149. Kasianowicz, J. J., Brandin, E., Branton, D. & Deamer, D. W. Characterization of individual polynucleotide molecules using a membrane channel. *Proc. Natl. Acad. Sci. USA* **93**, 13770–13773 (1996).

150. Kasianowicz, J. J., Henrickson, S. E., Weetall, H. H. & Robertson, B. Simultaneous multianalyte detection with a nanometer-scale pore. *Anal. Chem.* **73**, 2268–2272 (2001).

Describes how nanopores might be able to act as biosensors. This technology has incredible potential as a biogent sensor.

151. Relman, D. A. Genome-wide responses of a pathogenic bacterium to its host. *J. Clin. Invest.* **110**, 1071–1073 (2002).

152. Relman, D. A. Shedding light on microbial detection. *N. Engl. J. Med.* **349**, 2162–2163 (2003).

153. Davies, D. H. *et al.* Profiling the humoral immune response to infection by using proteome microarrays: High-throughput vaccine and diagnostic antigen discovery. *Proc. Natl. Acad. Sci. USA* **102**, 547–552 (2005).

154. Hertel, L. & Mocarski, E. S. Global analysis of host cell gene expression late during cytomegalovirus infection reveals extensive dysregulation of cell cycle gene expression and induction of Pseudomitis independent of US28 function. *J. Virol.* **78**, 11988–12011 (2004).

155. Kobayashi, S. D. *et al.* Bacterial pathogens modulate an apoptosis differentiation program in human neutrophils. *Proc. Natl. Acad. Sci. USA* **100**, 10948–10953 (2003).

Shows how innate immune cells can be used as early host-directed diagnosis and how various pathogens alter early responding cells.

156. Rubins, K. H. *et al.* The host response to smallpox: analysis of the gene expression program in peripheral blood cells in a nonhuman primate model. *Proc. Natl. Acad. Sci. USA* **101**, 15190–15195 (2004).

157. Waters, M. D. & Fostel, J. M. Toxicogenomics and systems toxicology: aims and prospects. *Nature Rev. Genet.* **5**, 936–948 (2004).

A good review on the field of toxicogenomics and explains how this field is evolving.

158. Gilfillan, L. *et al.* Taking the measure of countermeasures: leaders' views on the nation's capacity to develop biodefense countermeasures. *Biosecur. Bioterror.* **2**, 320–327 (2004).

Debates our readiness against a bioterrorist attack and reports the views of several key leaders regarding our capacity to develop solid biodefence countermeasures.

159. Mahanty, S. & Bray, M. Pathogenesis of filoviral haemorrhagic fevers. *Lancet Infect. Dis.* **4**, 487–498 (2004).

An in-depth review of filoviruses life cycle and pathogenesis.

160. Borio, L. *et al.* Hemorrhagic fever viruses as biological weapons: medical and public health management. *JAMA* **287**, 2391–2405 (2002).

161. Bausch, D. G. *et al.* Risk factors for Marburg hemorrhagic fever, Democratic Republic of the Congo. *Emerg. Infect. Dis.* **9**, 1531–1537 (2003).

162. Leroy, E. M. *et al.* Multiple Ebola virus transmission events and rapid decline of central African wildlife. *Science* **303**, 387–390 (2004).

163. Feldmann, H., Jones, S., Klenk, H. D. & Schnittler, H. J. Ebola virus: from discovery to vaccine. *Nature Rev. Immunol.* **3**, 677–685 (2003).

164. Geisbert, T. W. & Jahrling, P. B. Towards a vaccine against Ebola virus. *Expert Rev. Vaccines* **2**, 777–789 (2003).

165. Levine, M. M. New Generation Vaccines (ed. Dekker, M.) (Taylor & Francis, New York London, 2004).

166. Henderson, D. A. *et al.* Smallpox as a biological weapon: medical and public health management. Working Group on Civilian Biodefense. *JAMA* **281**, 2127–2137 (1999).

167. Garbutt, M. *et al.* Properties of replication-competent vesicular stomatitis virus vectors expressing glycoproteins of filoviruses and arenaviruses. *J. Virol.* **78**, 5458–5465 (2004).

168. Chen, R. T. & Lane, J. M. Myocarditis: the unexpected return of smallpox vaccine adverse events. *Lancet* **362**, 1345–1346 (2003).

169. Earl, P. L. *et al.* Immunogenicity of a highly attenuated MVA smallpox vaccine and protection against monkeypox. *Nature* **428**, 182–185 (2004).

170. Hsu, V. P. *et al.* Opening a *Bacillus anthracis*-containing envelope, Capitol Hill, Washington, D. C. : the public health response. *Emerg. Infect. Dis.* **8**, 1039–1043 (2002).

171. Friedlander, A. M. Textbook of Military Medicine (ed. Zajchuk, R.) 467–478 (U. S. Department of the Army, Surgeon General and the Borden Institute, Washington, DC, 1997).

A good review on *Bacillus anthracis* pathogenesis.

172. Brachman, P. S. Inhalation anthrax. *Ann. NY Acad. Sci.* **353**, 83–93 (1980).

173. Hall, A. S. *et al.* Comparison of noninvasive sampling sites for early detection of *Bacillus anthracis* spores from rhesus monkeys after aerosol exposure. *Mil. Med.* **164**, 833–837 (1999).

174. Meltzer, M. I., Damon, I., LeDuc, J. W. & Millar, J. D. Modeling potential responses to smallpox as a bioterrorist weapon. *Emerg. Infect. Dis.* **7**, 959–969 (2001).

175. Sandvig, K. & van Deurs, B. Transport of protein toxins into cells: pathways used by ricin, cholera toxin and Shiga toxin. *FEBS Lett.* **529**, 49–53 (2002).

176. Olsnes, S. & Kozlov, J. V. Ricin. *Toxicon* **39**, 1723–1728 (2001).

177. Endo, Y. & Tsurugi, K. The RNA N-glycosidase activity of ricin A-chain. The characteristics of the enzymatic activity of ricin A-chain with ribosomes and with rRNA. *J. Biol. Chem.* **263**, 8735–8739 (1988).

178. Lord, M. J. *et al.* Ricin. Mechanisms of cytotoxicity. *Toxicol. Rev.* **22**, 53–64 (2003).

179. Endo, Y. & Tsurugi, K. RNA N-glycosidase activity of ricin A-chain. Mechanism of action of the toxic lectin ricin on eukaryotic ribosomes. *J. Biol. Chem.* **262**, 8128–8130 (1987).

180. Greenfield, R. A. & Bronze, M. S. Prevention and treatment of bacterial diseases caused by bacterial bioterrorism threat agents. *Drug Discov. Today* **8**, 881–888 (2003).

A good source for currently available prophylactics and treatments against bacterial bioweapons.

181. Kozel, T. R. *et al.* mAbs to *Bacillus anthracis* capsular antigen for immunoprotection in anthrax and detection of antigenemia. *Proc. Natl. Acad. Sci. USA* **101**, 5042–5047 (2004).

182. Little, S. F., Ivins, B. E., Fellows, P. F., Friedlander, A. M. & 1997. Passive protection by polyclonal antibodies against *Bacillus anthracis* infection in guinea pigs. *Infect. Immun.* **65**, 5171–5175.

183. Little, S. F., Leppala, S. H., & Cora, E. Production and characterization of monoclonal antibodies to the protective antigen component of *Bacillus anthracis* toxin. *Infect. Immun.* **56**, 1807–1813 (1988).

184. Maynard, J. A. *et al.* Protection against anthrax toxin by recombinant antibody fragments correlates with antigen affinity. *Nature Biotechnol.* **20**, 597–601 (2002).

185. Sawada-Hirai, R. *et al.* Human anti-anthrax protective antigen neutralizing monoclonal antibodies derived from donors vaccinated with anthrax vaccine adsorbed. *J. Immune Based Ther. Vaccines* **2**, 5 (2004).

186. Brown, D. R., Lloyd, J. P. & Schmidt, J. J. Identification and characterization of a neutralizing monoclonal antibody against botulinum neurotoxin serotype F, following vaccination with active toxin. *Hybridoma* **16**, 447–456 (1997).

187. Casadevall, A. Passive antibody administration (immediate immunity) as a specific defense against biological weapons. *Emerg. Infect. Dis.* **8**, 833–841 (2002).

A review that covers antibody development for several biowarfare agents.

188. Chen, F. *et al.* Antibody mapping to domains of botulinum neurotoxin serotype A in the complexed and uncomplexed forms. *Infect. Immun.* **65**, 1626–1630 (1997).

189. Ferreira, J. L., Hamdy, M. K., McCay, S. G. & Zapata, F. A. Monoclonal antibody to type F Clostridium botulinum toxin. *Appl. Environ. Microbiol.* **56**, 808–811 (1990).

190. Kubota, T. *et al.* Epitope regions in the heavy chain of Clostridium botulinum type E neurotoxin recognized by monoclonal antibodies. *Appl. Environ. Microbiol.* **63**, 1214–1218 (1997).

191. Marks, J. D. Deciphering antibody properties that lead to potent botulinum neurotoxin neutralization. *Mov Disord* **19** (Suppl. 8), S101–S108 (2004).

192. Mullaney, B. P., Pallavicini, M. G. & Marks, J. D. Epitope mapping of neutralizing botulinum neurotoxin A antibodies by phage display. *Infect. Immun.* **69**, 6511–654 (2001).

193. Nowakowski, A. *et al.* Potent neutralization of botulinum neurotoxin by recombinant oligoclonal antibody. *Proc. Natl. Acad. Sci. USA* **99**, 11346–11350 (2002).

194. Pless, D. D., Torres, E. R., Reinke, E. K. & Bavari, S. High-affinity, protective antibodies to the binding domain of botulinum neurotoxin type A. *Infect. Immun.* **69**, 570–574 (2001).

195. Chanh, T. C. & Hewetson, J. F. Protection against ricin intoxication *in vivo* by anti-idiotype vaccination. *Vaccine* **13**, 479–485 (1995).

196. Chanh, T. C., Romanowski, M. J. & Hewetson, J. F. Monoclonal antibody prophylaxis against the *in vivo* toxicity of ricin in mice. *Immunol. Invest.* **22**, 63–72 (1993).

197. Lemley, P. V., Amanatides, P. & Wright, D. C. Identification and characterization of a monoclonal antibody that neutralizes ricin toxicity *in vitro* and *in vivo*. *Hybridoma* **13**, 417–421 (1994).

198. Lemley, P. V., Thalley, B. S. & Stafford, D. C. Prophylactic and therapeutic efficacy of an avian antitoxin in ricin intoxication. *Ther. Immunol.* **2**, 59–66 (1995).

199. Maddaloni, M. *et al.* Immunological characteristics associated with the protective efficacy of antibodies to ricin. *J. Immunol.* **172**, 6221–6228 (2004).

200. Olson, M. A. *et al.* Finding a new vaccine in the ricin protein fold. *Protein Eng. Des. Sel.* **17**, 391–397 (2004).

201. Poli, M. A., Rivera, V. R., Pitt, M. L. & Vogel, P. Aerosolized specific antibody protects mice from lung injury associated with aerosolized ricin exposure. *Toxicol.* **34**, 1037–44 (1996).

202. Smallshaw, J. E. *et al.* A novel recombinant vaccine which protects mice against ricin intoxication. *Vaccine* **20**, 3422–3427 (2002).

203. LeClaire, R. D. & Bavari, S. Human antibodies to bacterial superantigens and their ability to inhibit T-cell activation and lethality. *Antimicrob. Agents Chemother.* **45**, 460–463 (2001).

204. LeClaire, R. D., Hunt, R. E. & Bavari, S. Protection against bacterial superantigen staphylococcal enterotoxin B by passive vaccination. *Infect. Immun.* **70**, 2278–2281 (2002).

205. Burnett, J. C. *et al.* Conformational sampling of the botulinum neurotoxin serotype A light chain: implications for inhibitor binding. *Bioorg. Med. Chem.* **13**, 333–341 (2005).

206. Franz, D. R. in *Textbook of Military Medicine* (ed. Zajchuk, R.) 603–619 (US Department of the Army, Surgeon General and the Borden Institute, Washington DC, 1997).

Acknowledgements

The authors would like to thank M. J. Aman, R. Panchal, C. Whitehouse, B. Purcell, B. Stiles, R. Gussio and M. Hepburn for critical comments and substantial help in preparing this review. T. I. Nguyen for generating figure 1. In addition, we sincerely apologise to our esteemed colleagues whose work could not be included in

this review due to space limitations. The content of this review does not necessarily reflect the views or policies of the Department of Health and Human Services or US Army, nor does mention of trade names, commercial products or organizations imply endorsement by the US Government.

Competing interest statement

The authors declare no competing financial interests.

 **Online links**
FURTHER INFORMATION

Bioterrorism Resources:

<http://www-library.ncifcrf.gov/bioterrorism.asp>

CDC Emergency Preparedness & Response Site:

<http://www.bt.cdc.gov/>

Centers for Disease Control: <http://www.cdc.gov/>

Developmental Therapeutics Program NCI/NIH:

<http://dtp.nci.nih.gov/>

US Army Medical Research Institute of Infectious Diseases:

<http://www.usamriid.army.mil/>

US Department of State: <http://usinfo.state.gov/>

Access to this interactive links box is free online.